

Mathematical Modeling of Photovoltaic Thermal-Thermoelectric (PVT-TE) Air Collector

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ABSTRACT

Photovoltaic (PV) cell from solar energy is one of the most widely adopted renewable energy source and commercially available system that can be used in various applications. More appealing application of PV arrays used in thermoelectric (TE) device was it can convert solar thermal energy from temperature difference into electric energy to act as power generators. In this study, a theoretical model is developed by using conducting steady state energy analysis of a PVT-TE air collector. The matrix inversion method is used to obtain energy balance equation. The effect of various parameters also investigated. The mass flow rate of range 0.01 kg/s to 0.05 kg/s and solar intensity of 400 W/m², 600 W/m² and 800 W/m² was used to obtain outlet temperature, T_o in the range about 28.9°C to 43.7°C and PV temperature, T_p about 35.3°C to 60°C.

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1. INTRODUCTION

Solar energy is becoming increasingly attractive. It is an alternative and renewable energy resource, comes from the energy of the sun and serves as one of the most abundant permanent energy sources. Solar energy is free, clean, secure, and available on earth throughout the year. This form of clean energy is important to the world, especially during these times of high fossil fuel costs and environmental concerns arising from fossil fuel applications [1], [2], [3], [4], [5]. Furthermore, solar energy can be used in various applications such as thermal management using thermal collectors or electricity generation through photovoltaic (PV) cells. PV cell are semiconductor devices used to convert solar energy into electricity [6], [7], [8], [9], [10], [11]. To overcome the limitation of conversion efficiency of PV cell, photovoltaic thermal (PVT) was introduced which is the most commonly used method for active cooling that provide both thermal and electricity simultaneously [12], [13]. Beside that, by modifying the nonlinear I-V calculation which includes open circuit, extreme power and short circuit, the theoretical and simulation approach of the photovoltaic cell by Matlab-Simulink Situation can be evaluated to get a better performance [14], [15].

In addition to alternative sources, thermoelectric (TE) devices have been arise as other encouraging environmental friendly applications for heat pump and power generators [16]. Thermoelectric generator (TEG) have benefits such as compressed in size, mild in weight, high dependability, no working fluid and no mechanical moving parts. Furthermore, direct current (DC) electric sources such as fuel cells, car DC electric sources and PV can be used for powered the thermoelectric [17].

A contemporary idea of conversion of thermal energy into electricity directly using TE has been present several years ago. The integration of TEs with PV systems allows used of the PV by-product heat to generate additional electricity, therefore improving the power generation of the system [18]. Mojumder et al. [19] proposed single pass PVT air collector system where a number of thin rectangular fins was establish for heat dissipation. The energy balance equation was analytically derived for each component of the design and

the thermal and electrical efficiency of PVT system were calculate by conducting measurement of different number of fins (0-4), mass flow rate (0.02-0.14 kg/s) and solar radiation (200-700W/m²). The result show that by using four fins at mass flow rate 0.14 kg/s and 700 W/m² of solar radiation, the maximum PV efficiency and thermal efficiency acquired of 13.75% and 56.19% respectively. A mathematical model was develop by Khelifa et al. [20] with a thermal system for water heating. This study also includes theoretically and experimentally the hybrid PVT collector. The energy balances of the model and the coupled differential equations obtained are solved using finite differential method. Different parameters used different method to analysis the data in hybrid PVT collector such as fluid flow, heat transfer in the module, heat transfer between the photovoltaic and coolant, and effect of radiation. Kossyvakis et al. [21] examined experimentally the performance of a tandem PV-TEG hybrid utilize poly-Si as well as dye-sensitized solar cells. The performance effect is tested using different thermoelement geometry which the shorter thermoelements increases the power output levels when considered the conditions of actual operation. Zhu et al. [22] build a combination of PV-TE technologies which effectively increase the total power output by delivered a large temperature difference across the TE module with controlled heat flow. The theoretically and numerically temperature distribution was calculated for design PV-TE hybrid system. An advance of theoretical model was studied by Zhang et al. [23] for evaluating the efficiency of concentrating PV-TE hybrid system by using different type of PV cell. Rezania & Rosendahl [24] studied on CPV system integrated with TEGs. They investigate feasibility of hybrid system of concentrated photovoltaic-thermoelectric (CPV/TEG) system over wide range of solar concentration and different type of heat sinks. They reported that the efficiency of CPV-only system is lower than the CPV/TEG system that consists of TE materials $ZT \approx 1$.

From previous studies, most theoretical studies only use the common equation of the Hottel-Whiller equation. Therefore, the aim of this study is to propose a new theory approach by using the equilibrium equation in the mathematical model to predict the temperature and output temperature of the PV. Furthermore, this new theory also can minimize the error in this theoretical study. According to author's knowledge, it can be concluded that the study of thermal equilibrium on the PVT system is limited and studies on PVT-TE hybrids have not been studied by any previous researchers.

2. MATHEMATICAL MODELING

The cross-sectional view of PVT-TE air collector are arranged as shown in Fig. 1 which included air channels frequently present at the back of a PV laminate allowing naturally or forced open air to flow and extract accumulated heat over convective heat transfer. A series of analytical solutions were deliberated based on the flow model and thermal distribution in the energy balance equations for each component of the PVT systems. The following assumptions based on [25], [26], [27].

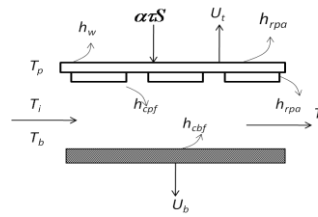


Figure 1. Schematic of Heat Transfer Coefficients in a PVT-TE Air Collector

The energy balance equations at steady state for PVT-TE air collector is given as
For the PV is

$$\tau\alpha S = U_t(T_p - T_a) + h_{cpf}(T_p - T_f) + h_{rpb}(T_p - T_b) + \eta_{PV}S + Q_n \quad (1)$$

For the air flow channel is

$$mC(T_o - T_i) = h_{cpf}(T_p - T_f) + h_{cbf}(T_b - T_f) + Q_n \quad (2)$$

For the back plate is

$$h_{rpb}(T_p - T_b) = h_{cbf}(T_b - T_f) + U_b(T_b - T_a) \quad (3)$$

Where,

$$Q_n = NA_n h_{rpb} \eta_{TEG} (T_p - T_f) \quad (4)$$

$$U_b = \frac{k_t}{l_t} \quad (5)$$

$$U_i = \left(\frac{1}{h_w + h_{rpa}} \right)^{-1} \quad (6)$$

$$h_{rpb} = \frac{\sigma (T_p + T_b) (T_p^2 + T_b^2)}{\left(\frac{1}{\varepsilon_p} + \frac{1}{\varepsilon_b} - 1 \right)} \quad (7)$$

$$h_{rpa} = \varepsilon_p \sigma (T_p^2 + T_{sky}^2) (T_p - T_{sky}) \quad (8)$$

$$T_{sky} = 0.0522 T_a^{1.5} \quad (9)$$

where ε_p , σ , T_a , T_{sky} , and T_p are the emissivity of PV, Stefan Boltzman constant, ambient, sky and PV temperature, respectively.

The convective heat transfer coefficients are given as:

$$h = \frac{k}{D_h} Nu \quad (10)$$

which,

$$D_h = \frac{4Wd}{2(W+d)} \quad (11)$$

Where W , d , D_h are the width, high, equivalence diameter of the channel, k is air thermal conductivity, and Nu is Nusselt number. Nusselt numbers are given as, for $Re < 2300$ (laminar flow region):

$$Nu = 5.4 + \frac{0.00190 \left[Re Pr \left(\frac{D_h}{L} \right) \right]^{1.71}}{1 + 0.00563 \left[Re Pr \left(\frac{D_h}{L} \right) \right]^{1.17}} \quad (12)$$

For $2300 < Re < 6000$ (transition flow region):

$$Nu = 0.116 (Re^{2/3} - 125) Pr^{1/3} \left[1 + \left(\frac{D_h}{L} \right)^{2/3} \right] \left(\frac{\mu}{\mu_w} \right)^{0.14} \quad (13)$$

For $Re > 6000$ (turbulent flow region):

$$Nu = 0.018 Re^{0.8} Pr^{0.4} \quad (14)$$

where, Re and Pr are the Reynolds and Prandtl number given as:

$$\text{Re} = \frac{mD_h}{A_{ch}\mu} \quad (15)$$

$$\text{Pr} = \frac{\mu C}{k} \quad (16)$$

The mean air temperature as follow:

$$T_f = \frac{(T_i + T_o)}{2} \quad (17)$$

The physical properties of air are given as [24], [25], [26], [27]:
thermal conductivity

$$k = 0.02624 + 0.0000758(T - 27) \quad (18)$$

Viscosity

$$\mu = [1.983 + 0.00184(T - 27)]10^{-5} \quad (19)$$

specific heat

$$C = 1.0057 + 0.000066(T - 27) \quad (20)$$

Density

$$\rho = 1.1774 - 0.00359(T - 27) \quad (21)$$

Heat transfer coefficients are calculated corresponding to the initially guessed temperature values. In this study, the air, ambient, PV and back plate temperatures of the first section were initially predicted and specified, except those of the PV, which was set to 30°C above the ambient temperature. For back plate and air temperature in channel were set 20°C and 10°C above the ambient temperature. In order to fulfill the complete process, the major design parameters are given as $L = 0.54$ m, $W = 0.53$ m, $\alpha = 0.9$, $\tau = 0.92$, $\varepsilon_p = 0.7$, $\varepsilon_b = 0.9$, $T_a = T_i = 27^\circ\text{C}$ and $V = 1$ m/s.

For simplicity, Eq. (1) to (3) can be presented in a 3×3 matrix form.

$$[A][T] = [B] \quad (22)$$

$$\begin{bmatrix} X_1 + Y_1 & -h_{cpf} + Y_1 & -h_{rpb} \\ h_{cpf} + Y_1 & X_3 & h_{cpf} \\ h_{rpb} & h_{cbf} & X_5 \end{bmatrix} \begin{bmatrix} T_p \\ T_f \\ T_b \end{bmatrix} = \begin{bmatrix} X_2 \\ X_4 \\ X_6 \end{bmatrix} \quad (23)$$

Where

$$X_1 = U_t + h_{cpf} + h_{rpb} \quad (24)$$

$$Y_1 = (Q_n A_n h_{cpf} \eta_{TEG}) \quad (25)$$

$$A_n = A_{TEG} + (2HL) \quad (26)$$

$$X_2 = \alpha \pi S + U_t T_a - \eta_p S \quad (27)$$

$$X_3 = -(2h_{cpf} + Y_1 + 2mC) \tag{28}$$

$$X_4 = -2mCT_i \tag{29}$$

$$X_5 = -(h_{cpf} + h_{rpb} + U_b) \tag{30}$$

$$X_6 = -U_b T_a \tag{31}$$

Referring to Eq. (22), the temperature vector can be calculated using matrix inversion form by Excel

$$[T] = [A]^{-1} [B] \tag{32}$$

In this study, an adequate accumulation for T_p , T_f , and T_b was attained in three to four iterations after outlet temperature resolved using Equation (17).

3. RESULT AND DISCUSSION

The result of this study show the effect of changing mass flow rate and variable solar radiations on the outlet temperature, T_o and PV temperature, T_p on the performance of PVT-TE air collector system. The comparison of theoretical result between T_o and T_p was established shown in Figure 2.

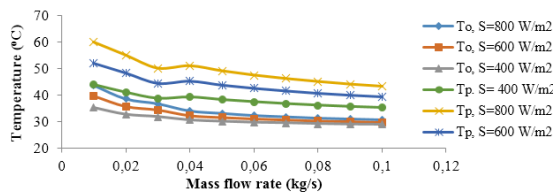


Figure 2. Variation Solar Intensity of T_o and T_p Versus Mass Flow Rate

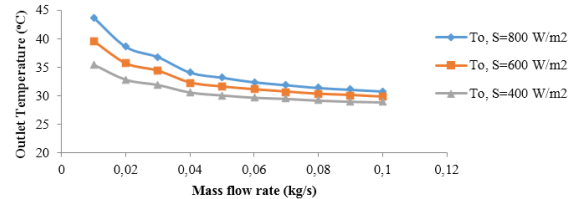


Figure 3. Variation Solar Intensity of T_o Versus Mass Flow Rate

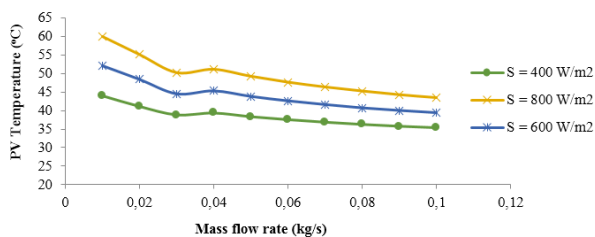


Figure 4. Variation Solar Intensity of T_p Versus Mass Flow Rate

A theoretical prediction was obtained represented in Fig. 3 and 4 by substituting the specified value of collector inlet temperature (T_i), ambient temperature (T_a), and other parameters in the information above into the suitable equations developed for T_o and T_f . The value ranges from 28.9°C to 43.7°C for the system output temperature. It show that the gain in produced thermal energy.

T_o and T_p obtain at higher solar radiation was due to more amount of incident solar energy converted into heat. The energetic behaviour of PVT also affect by solar radiations which is the most important external parameter for TE solar systems. At the highest air velocity in channel makes a higher heat convection effect, which offers the maximum heat gain. The maximum T_o and T_p were obtained about 43.7°C and 60°C respectively for 90 number of thermoelectric at 0.01kg/s of mass flow rate and 800W/m² of solar radiation. Thermoelectric used as fins has better electrical and thermal efficiency compared to the design without fins.

In addition, PV top, rear surface, collector back wall and outlet air temperature were significantly affected by fin numbers and mass flow rates.

4. CONCLUSIONS

The improvement of the overall generation efficiency of the PVT-TE air collector system was increased compared to that of single PV panel. A series of parameters on the PVT-TE air collector system of solar energy utilization have been analyzed and the effects towards the systems also studied. It can be concluded that temperature is the dominant factors among this parameter which affect the conversion efficiency of such hybrid systems. In addition, it is also important to select suitable value of the convection heat transfer coefficient and concentrated ratio to maintain a larger temperature gradient of the TE module. In addition, the electrical output of the PV module at the initial operating temperature should be examined in order to provide more clear view on the feasibility of such system before establishing the integration of the TE device.

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Nurul Syakirah Nazri obtained M.Sc (2014) in applied physics and currently is candidate Ph.D in University Kebangsaan Malaysia (UKM), Malaysia. Her current research focuses on renewable energy, especially photovoltaic thermal-thermoelectric (PVT-TE) hybrid system, and solar drying system.



Ahmad Fudholi, Ph.D, M.Sc obtained his S.Si (2002) in physics. 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). After his master he became Research Assistant at UKM up to 2012. After his Ph.D (2012) 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 (13 grant/ project) in 2014-2017 involved. More than 25 M.Sc project supervised and completed. Until now, he managed to supervise 5 Ph.D (4 main supervisor and 1 Co. supervisor), 2 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, photovoltaic thermal (PVT) systems and solar drying systems. He has published more than 100 peer-reviewed papers, which 25 papers in ISI index (20 Q1, impact factor more than 3) and more than 50 papers in Scopus index, 10 more currently accepted manuscript, 20 more currently under review, and 2 book chapters. Addition, he has published more than 70 papers in international conferences. His total citations of 609 by 419 documents and h-index of 12 in Scopus (Author ID: 57195432490). His total citations of 1132 and h-index of 19 in google scholar. He is appointed as reviewer of high impact (Q1) journal such as *Renewable and Sustainable Energy Reviews*, *Energy Conversion and Management*, *Applied Energy*, *Energy and Buildings*, *Applied Thermal Engineering*, *Energy*, *Industrial Crops and Products*, etc. He is appointed as reviewer of reputation journals such as *Drying Technology*, *International Journal of Green Energy*, *Biosystem Engineering*, *Journal of Sustainability Science and Management*, *Journal of Energy Efficiency*, *Sains Malaysiana*, *Jurnal Teknologi* etc. He is also appointed as editor journals. He has received several awards such as Gold Medal Award at the International Ibn Al-Haytham's Al-Manazir Innovation and Invention Exhibition 2011, Silver Medal Award at the International Technology EXPO (ITEX) 2012, Silver Medal Award at the Malaysia Technology Expo (MTE) 2013, Bronze Medal Award at International Exposition of Research and Invention (PECIPTA) 2011, also 2 Bronze Medal Award at PECIPTA 2017. He was also invited as speaker: Workshop of Scientific Journal Writing; Writing Scientific Papers Steps Towards Successful Publish in High Impact (Q1) Journals.



Prof. Dr. Mohd Hafidz Ruslan currently is the Deputy Director and Head of Postgraduate Studies of the Solar Energy Research Institute (SERI) UKM, Malaysia. His current research focuses on solar energy, especially solar thermal technology, heat pump system, solar water heating and solar drying systems. He has published more than 150 peer-reviewed papers in ISI and Scopus index. Addition, he has published more than 100 papers in international conferences. His total citations of 1541 by 1077 documents and h-index of 22 in Scopus index (Author ID: 6504666472). His total citations of 2564 and h-index of 27 in google scholar index.



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. His MS thesis was on Solar Absorption Cooling System and the PhD dissertation was about the Double-Pass Photovoltaic Thermal Solar Collectors. Upon graduation, he has been appointed as an Assistant Professor at the Department of Mechanical and Materials Engineering, Universiti Kebangsaan Malaysia (National University of Malaysia). He was promoted to the post of Professor of Renewable Energy in the Department of Mechanical and Material Engineering, at the Universiti Kebangsaan Malaysia (the National University of Malaysia) in 2001 and currently is the Director of the Solar Energy Research Institute in the same university since 2005. He has been involved in the field of renewable energy for more than 25-years. His main contributions are in solar radiation modeling and resource assessment, advanced solar photovoltaic systems (grid-connected photovoltaic, solar powered regenerative fuel cell, solar hydrogen production, thin film silicon solar cell) and advanced solar thermal systems (solar cooling, solar heat pump, solar assisted drying, combined photovoltaic thermal or hybrid collector). 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, TIKTA and UNESCO. He has published over 800 research papers in journals and conferences (SCOPUS h index = 49, no. of citation = 8001) (Google Scholar h index = 60, no. of citation = 13473). A total of 32 MSc (coursework), 15 MSc (research mode) and 40 PhD candidates from various countries such as Bangladesh, Iran, Iraq, Algeria, Libya, Indonesia, Nigeria, Oman, Yemen, Malaysia and Jordan have graduated under his supervision. He has delivered keynotes and plenary speeches at national and international conferences on renewable energy in Malaysia, China, India, Iraq, Iran, France, Greece, Morocco, United Kingdom, United States, Hungary, Egypt, Libya, United Arab Emirates, Syria, Saudi Arabia, Bahrain, Indonesia, Thailand, Philippines, Japan, Singapore, Germany, Holland, Italy, Maldives, and Cambodia. 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 (Canada International Development Agency), 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 the Faculty of Built Environment, University of Nottingham, United Kingdom (2009 -2013). In addition, he has been appointed as the associate editors of the Journal of Renewable Energy (2005 – 2010) and Journal of Sustainable Cities and Society published by Elsevier Ltd, and Journal of Energy, Hindawi. Journal of Sustainable Energy and the Environment (Thailand), Jordan Journal of Mechanical and Industrial Engineering (JJMIE) (Jordan), International Journal of Thermal and Environmental (Canada) and Palestine Technical University Research Journal (Palestine). 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 (PMP) in 2003 and the Dato' Paduka Mahkota Perak (DPMP) in 2013. He was conferred as a Fellow of the Malaysia Academy of Sciences (FASc) in 2011. Promoting renewable energy technology to the communities and industries has always been his passion. He has developed and delivered solar dryers for fish and seaweeds in Karkor Cambodia and Semporna Malaysia respectively. In addition, he has developed a cottage industry for manufacturing of photovoltaic panels in Kuala Trengganu. He has also delivered the first pico hydro system for an orang asli community in Kampung Tuel, Kelantan. He has designed and commissioned the first large scale solar assisted hot water system for a 1000 bed hospital in Malaysia and also a solar assisted drying system for old palm fronds for a palm oil factory in Malaysia.