



Effect of New Ellipse Design on the Performance Enhancement of PV/T Collector: CDF Approach

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Abstract. Photovoltaic and thermal collectors are combined via a photovoltaic/thermal (PV/T) collector system to increase collector efficiency. The efficiency of photovoltaic collectors is known to decrease when ambient temperature increases and vice versa. PV/T collector systems function by absorbing the heat gained from the sun via photovoltaic panels and by converting this heat into electrical energy. Simulations CFD have been investigated to explore the impact of different mass flow rates against photovoltaic and thermal efficiencies of PVT collector using FVM. New ellipse design of collectors have been modeled and investigated to generate hot water and electricity. In this simulation, the absorber collectors were assumed to be attached underneath the photovoltaic (PV) module, and water is used as a heat transfer medium in absorber collectors. The results shown that new ellipse absorber collector generates a combined PV/T efficiency of 74.3% with electrical efficiency of 13.78%. The efficiency of the PV/T system should be improved further by developed the surfaces between the absorber and solar panel (PV module). However, different types of PV cells, such as amorphous silicon cells with black mat surface properties, should be used to improve the thermal absorption of PV/T systems.

Highlights: (i) A three-dimension hybrid photovoltaic/thermal solar collector module was performed in CFD software; (ii) The results agree with those obtained through steady-state characterization; (iii) The simultaneous use of new ellipse design of absorber, which absorbs much more thermal energy compared to other normal designs, increase thermal and electrical efficiency significantly.

Keywords. Absorber Collector, CFD, Energy, Photovoltaic/Thermal (PV/T), Thermal and Electrical Efficiency.

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1. Introduction

A hybrid PV/thermal (PV/T) system is a system in which heat from the PV panel is removed by a working fluid and can simultaneously convert solar energy into electrical and thermal energy. Compared with separate PV or thermal systems, the hybrid system has several advantages, including high total energy conversion efficiency, low cost, and small installation areas. Solar PV/T applications can provide heat and electricity. To achieve high efficiency and significant amounts of power and heat from PV/T systems, PV cells should be cooled, particularly in areas with hot

and humid climates. Thus, the overall efficiency of solar energy is improved. Fluid-based PV/T collectors are more desirable and effective than existing air systems. Temperature fluctuations in the base fluid (water) of PV/T are significantly less than those in the air-based PV/T collectors, which are subjected to varying solar irradiance levels. Over the past decades, various PV/T systems or collectors that use water as working fluid for heat removal have been numerically and experimentally studied.

Problems such as low PV efficiency, architectural uniformity, and limited space on the roof for the installation of the separate system have become important factors that influenced the idea of combining the PV/T system into one complete system. One of the major disadvantages of PV cell, besides the high cost, is the problem with low efficiency (Sok et al., 2010). Research in this field was carried out in the mid-1970s to early 1980s. The earliest study on the PV/T water collector was performed by Florschuetz (1979) who extended the Hottel and Whillier (1955) to analyze the combination of PV/T flat plate collector. As mentioned by Zondag et al. (2002), combining the PV/T collector will provide solutions to problems such as PV efficiency increasing due to the cooling effect, provide more architectural uniformity by aesthetic design, and finally, minimize the usage of space on the roof. These will reduce the payback period.

2. Previous Research

Wolf (1976) first investigated flat plate PV/T fluid systems and dissected the effect of the mix of heating and PV power systems for homes. He concluded that the system is feasible and cost effective. The Hottel-Whillier model is utilized to use the mix of PV and thermal flat plate collectors with the conventional hot water system and PV panel to minimize establishment usage. (Hottel and Whillier, 1958).

Zondag et al. (2001) and Jong (2001) have conducted a series of comparisons between different types of PV/T design and different types of thermal systems. Their experiments generally investigated the covered and uncovered PV/T and thermal systems. Their studies indicated that an uncovered PV/T shows improved efficiency with the use of PV/T for low-temperature ground storage integrated with a heat pump.

Zondag (2008) reviewed various concepts of combined PV-thermal collector technologies by introducing and evaluating nine different designs, ranging from the complicated to the simple, in order to investigate the maximum yield. They concluded that the design of the channel below the transparent PV, with its PV-

on-sheet and tubes design, gives the best efficiency overall.

Performance simulation of PV/T collectors with seven new design configurations of absorber collectors design has been studied by Ibrahim et al. (2009) and conclude that the best design configuration is the spiral flow design with a thermal efficiency of 50.12% and cell efficiency of 11.98%.

PV/T collectors have been recently utilized in different industries, and such collector motivated researchers in different fields of study perform experimental and numerical methods (Al-Shamani et al., 2015; Al-Shamani et al., 2014; Bergene and Løvvik, 1995; Chow, 2003; Coventry, 2005; Cox and Raghuraman, 1985; Huang et al., 2011; Kadhim et al., 2013; Mbewe et al., 1985; Skoplaki and Palyvos, 2009; Takashima et al., 1994; Tripanagnostopoulos, 2007).

3. Methodology

3.1 Governing Equations

The governing equations (continuity, momentum, and energy) must be set to complete CFD analysis of the PV/T collector. The phenomenon under consideration was governed by the steady 3D computational domain of the continuity, time-averaged incompressible Navier-Stokes equations, and energy equation. In the Cartesian tensor system, these equations could be written as (Eiamsa-ard and Promvonge, 2008).

3.2 Energy Analysis of PV/T Collector

PV efficiency decreases when the temperature of the cells increases. The efficiency of the photovoltaic cells depends on temperature (Duffie and Beckman, 1991). Further, the performance of PV/T collectors can be depicted by the combination of efficiency expression. It is comprised of the thermal efficiency η_{th} and the PV efficiency η_{el} , which usually includes the ratio of the useful thermal gain and electrical gain of the system to the incident of solar irradiance on the collector's gap within a specific time or period. As shown in Equation 1, the total efficiency of η overall is used to evaluate the overall performance of the system (Duffie and Beckman, 1991).

$$\eta_{\text{overall}} = \eta_{\text{th}} + \eta_{\text{pv}} \quad 1$$

The thermal performance of the PV/T collector is influenced by the parameter of the system design and operating conditions. In this study, the system was analyzed with various configurations of ambient temperature, solar radiation, and flow rate conditions. Based on this assumption, the thermal performance η_{th} of the PV/T unit was evaluated for its thermal and PV performance. Thus, the derivation of the efficiency parameters based on the Hottel-Whillier equations (Hottel and Whillier, 1958) was used. The thermal efficiency (η_{th}) of the conventional flat plate solar collector can be calculated using the Equation 2 below (Duffie and Beckman, 1991):

$$\eta_{\text{th}} = \frac{Q_u}{G} \quad 2$$

Using Equation 2, the useful heat collected (Q_u) by the water in terms of its temperature rise can be explored further using Equation 3 (Duffie and Beckman, 1991):

$$Q_u = \dot{m} C_p (T_o - T_i) \quad 3$$

The difference between thermal heat losses and the absorber solar radiation was identified using the Hottel-Whillier equations (Hottel and Whillier, 1955), then the energy balance equation for the collector is identify as in Equation 3:

$$Q_u = A_c F_R [S(\tau\alpha) - U_L (T_i - T_a)] \quad 4$$

From Equation 4, the solar irradiance absorbed by a collector per unit area of absorber S is equal to the difference between the incident of solar irradiances and optical loses. The S can be identified using Equation 4.1:

$$S = (\tau\alpha)_{\text{pv}} G_T \quad 4.1$$

The heat removal efficiency factor (FR) can be calculated as in Equation 5 (Duffie and Beckman, 1991):

$$F_R = \frac{\dot{m} C_p}{A_c U_L} * \left[1 - \exp \left(- \frac{A_c U_L F'}{\dot{m} C_p} \right) \right] \quad 5$$

The corrected fin efficiency (F') is calculated using

$$F' = \left[\frac{\frac{1}{U_L}}{W \left[\frac{1}{U_L (D + (W - D) F)} + \frac{1}{c_b} + \frac{1}{\pi D_i h_{fi}} \right]} \right] \quad 6$$

Therefore, the efficiency factor F can be calculated using Equation 12:

$$F = \frac{\tanh \left[M \left(\frac{W - D}{2} \right) \right]}{M \left(\frac{W - D}{2} \right)} \quad 7$$

$$\text{Where } M = \sqrt{\frac{U_L}{(K_{\text{abs}} L_{\text{abs}}) + (K_{\text{pv}} + L_{\text{pv}})}}$$

The useful heat gain of the solar collector can be calculated by rearranging Equation 7, and the thermal efficiency of the collector can be expressed using Equation 8 (Vokas et al., 2006):

$$\eta_{\text{th}} = F_R (\tau\alpha) - F_R U_L \left(\frac{T_i - T_a}{G_T} \right) \quad 8$$

The temperature-dependent electrical efficiency of the PV panel (η_{el}) is expressed as follows (Tiwari and Sodha, 2006):

$$\eta_{\text{el}} = \eta_r (1 - \beta (T_{\text{pm}} - T_r)) \quad 9$$

Where η_{el} is the electrical efficiency, η_r is the reference efficiency of the PV panel ($\eta_r = 0.14$), β is the temperature coefficient ($^{\circ}\text{C}0.0045 \text{ }^{\circ}\text{C}^{-1}$), T_{pm} is the temperature of the solar cells (K), and T_r is the reference temperature.

3.3 Design Configurations of the Absorber

As the PV cells in the PV module are exposed to the sun, they generate electricity while absorbing heat, causing the absorber to increase its temperature. During this time, the water fluid

passing inside the absorber tubes is heated because of the contact underneath the PV module. The water flows along the absorber through a manifold and pipes before being finally fed to a water tank. The absorbers are equipped with an inlet and outlet at opposite ends of the hollow tubes, which ensure that the trapped water in the absorber can be released. The system is considered a closed-loop system, wherein the fresh and cool water that enters the round tubes is heated continuously. The collector conceptual designs used in this study are shown in Figure 1, comprising three new design configurations.

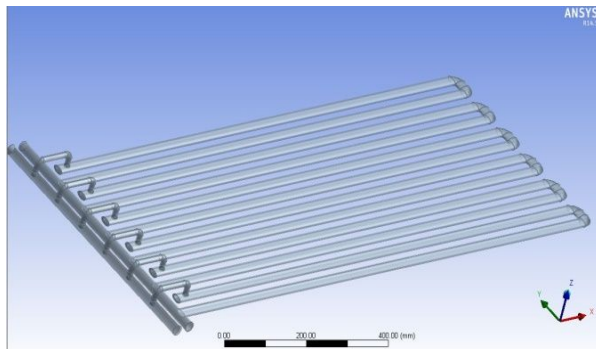


Figure 1: New Ellipse Absorber Design for PV/T Collector

3.4 Boundary Conditions

Appropriate boundary conditions are emphasized on the CFD domain as the physics of the problem. Inlet boundary conditions are specified as velocity inlet conditions. The outflow boundary condition is applied at the outlet. Wall boundary conditions are used to bind fluid and solid regions. At the wall, velocity components are set to zero in accordance with the no-slip and impermeability conditions that exist in viscous flow models. The interface between the water and absorber tube is characterized as the wall with coupled condition to conjugate heat exchange from the absorber tube to water. A shifting high temperature flux comparable to the solar insolation is connected at the top surface of the PV panel. The outer surface of the absorber tube is characterized as the wall with zero heat flux condition that affects insulated conditions.

Table 1

Characteristics of PVT collector

Ambient temperature	T_a	297 K
Inlet fluid temperature	T_i	300 K
Collector width	b	0.555 m
Tube spacing	W	0.02 m
Collector parameter	P	3.3 m
Collector area	A_c	0.875 m ²
Number of glass cover	N	1
Emissance of glass	ε_g	0.88
Emissance of plate	ε_p	0.95
Tilt (slope)	$^\circ$	14
Fluid flow rate	$\dot{m}_{dot}$	0.068 kg/s
Fluid thermal conductivity	k_{fluid}	0.613
Back insulation conductivity	C_p	4180
Specific heat	k_b	0.045 W/m ² K
Back insulation thickness	L_b	0.05 m
Insulation conductivity	k_e	0.045 W/m ² K
Edge insulation thickness	L_e	0.025 m
Absorber conductivity	k_{abs}	51 W/m ² K
Absorber thickness	L_{abs}	0.002 m
Fin conductivity	k_f	84 W/m ² K
Fin thickness	δ	0.0005 m
Heat transfer coefficient from cell to absorber	h_{ca}	45 W/m ² K
Heat transfer inside tube	h_{fi}	333 W/m ² K
Transmittance	τ	0.88
Absorptance	α	0.95

4. Results and Discussion

In order to numerically evaluate the performance of the PV/T Collector, the whole day numerical results are shown in Figure 2 to Figure 4, which illustrate solar irradiance, ambient temperature, PVT module temperature, and outlet water temperature. According to Figure 2, the maximum outlet water temperature from the ellipse design absorber reached approximately 55.53 °C, whereas the maximum PV temperature reached approximately 59.86 °C under the same conditions. Heat loss between the PV/T collector and environment was altogether higher than that between the conventional solar collector and environment. Hence, the thermal effectiveness of the PV/T collector was marginally lower than that of the conventional solar collector because of the expanded heat-loss coefficient.

Based on Figure 2 and the equations of PVT energy balance, the electrical PVT power,

thermal PVT power, and the overall PV/T power over daytime were determined.

Figure 3 shows the trends of solar radiation, PV, thermal, and PV/T energy for the whole day. PV, thermal, and PV/T energy varied continually with increasing solar irradiance and time. The results indicated that the PV, thermal, and PV/T energies used for the PVT collector varied (27.24- 93.70) W, (158.68- 630.67) W, and (185.92- 724.37) W, respectively, at a mass flow rate of 0.068 kg/s as shown in Figure 3.

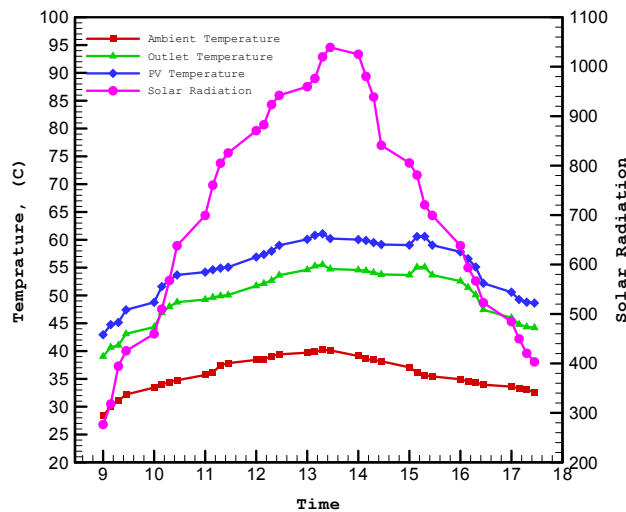


Figure 2: Hourly solar radiation and hourly mean temperature of (ambient, PVT collector, and water outlet) over daytime

Figure 4 illustrates the variation in the reference PV module efficiency and PV/T efficiency (PV, thermal, and overall) with hourly solar radiation over daytime with the ellipse absorber flow and a mass flow rate of 0.068 kg/s. The results showed that the reference PV module efficiency varied between 7.88-9.52%, while the PV efficiency was 12.55- 13.78%, thermal efficiency was 57.40- 61.45 %, and overall PVT efficiency was 71.18- 74.30%.

The total of both efficiencies, which is known as PV/T efficiency, was used to evaluate the overall performance of the system.

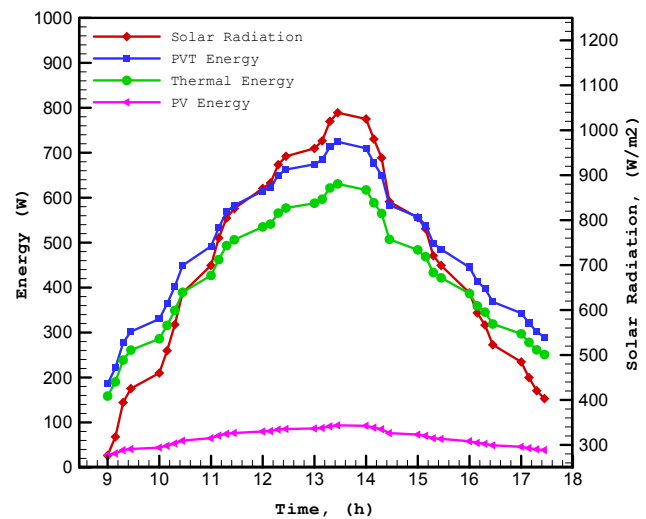


Figure 3: Mean power variation of PVT with hourly solar radiation, $\dot{m}=0.068$ kg/s over daytime

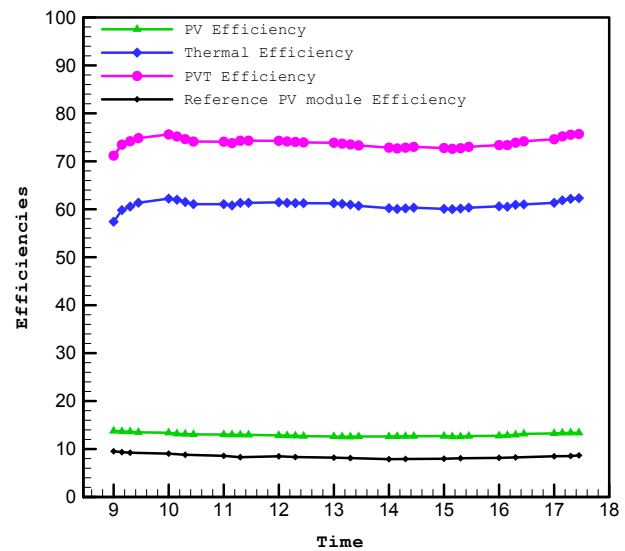


Figure 4: Efficiency variation of reference PV module and PVT (PV, thermal and overall) with hourly solar radiation, $\dot{m}=0.068$ kg/s over daytime

Figure 5 and Figure 6 show the contour profile of temperature distributions on the PVT-Ellipse absorber. It is clear that the temperature profile is uniform. Figure 7 shows the streamline velocity contour of the PVT-Ellipse absorber, and it is also clear to see the velocity moving from inlet to outlet and drop the temperature of PV module.

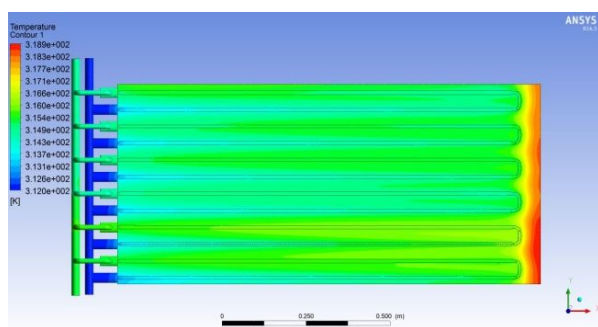


Figure 5: Isotherms profile of ellipse absorber design with PV module

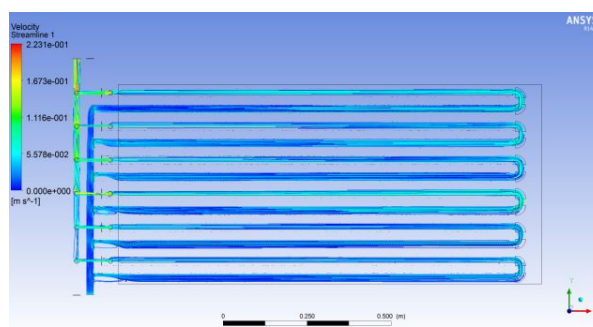


Figure 7: Streamlined profile of ellipse absorber design

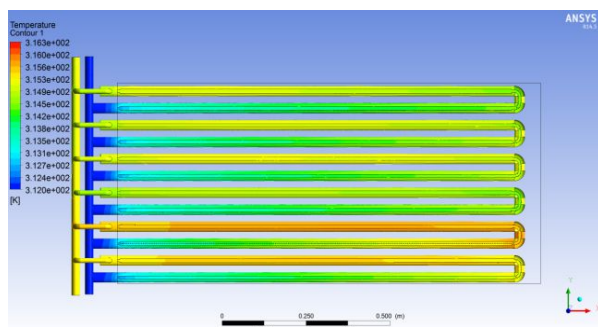


Figure 6: Isotherms profile of ellipse absorber design

5. Conclusion

Solar cells generate large amounts of electricity when large amounts of solar irradiance are received. However, the efficiency drops when the temperature of solar cells increases. Hybrid PV/T collectors can solve this problem. The PV/T collector with a new ellipse absorber design exhibited effective performance in cooling as well as high electrical and thermal efficiency. The PV and thermal production of a PV/T hybrid system increased with decreasing temperature of the environment. At a mass flow rate of 0.068 kg/s, electrical PV efficiency of 13.78% and PV/T efficiency of 74.3% was achieved.

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