Numerical Study on the Characteristics of a Specially Designed Rectangular Tube Absorber Photovoltaic Thermal Collector (PVT)

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Abstract: - The electrical efficiency of a photovoltaic (PV) cell decreases as it temperature increases. Since PV cells must be arranged in direct sunlight to produce electricity, heating is inevitable. A heat exchanger can be adapted to a PV cell to extract heat and hence increase the conversion efficiency while using heat absorbed from the cells for secondary applications. The thermal system consists of a rectangular aluminum reservoir that is mounted to the backside of PV panels, through which water flow. In this study, the solution for this was by adding a cooling system to the photovoltaic panel. The purpose of this study was to cool the solar cell in order to increase its electrical efficiency and also to produce heat energy in the form of hot water. The rectangular tube absorber was located at the back side of a standard photovoltaic panel. The simulation results shows that the Rectangular tube absorber collector generates combined PV/T efficiency of 64.8% with electrical efficiency of 11.4% at ambient temperature set between 28.6 to 33.55°C, fluid flow rate at 0.045kg/s and solar radiation between 700 to 800 W/m^2. It is recommended for PV/T system to further improve its efficiency by optimizing the contact surfaces between the solar panel (photovoltaic module) and the absorber collector underneath.

Key-Words: - Photovoltaic/Thermal (PV/T), Absorber Collector, Energy, Thermal and Electrical Efficiency.

1 Introduction

The advent of the oil crisis in the early 1970s and the global environment concerns in the nineties forced many to look for renewable and alternative clean energy sources. Therefore, an ingenious method of solar energy conversion must be developed and used as an alternative in the most vulnerable applications of fossil fuels. Biomass, solar energy, and wind energy are the world's most abundant permanent sources of energy; they are also important and environmentally compatible sources of renewable energy [1].

Energy is a thermodynamic quantity that is often understood as the capacity of a physical system to perform the work. Aside from its physical meaning, energy is vital for our relations with the environment. Life is directly affected by its energy and consumption. Energy resources based on fossil fuels are still dominant with the highest share in global energy consumption; however, clean energy generation is crucial because of the growing significance of environmental issues. Solar power is a key item in clean energy technologies because it provides an unlimited, clean, and environmentally friendly energy. Moreover, the other forms of renewable energy primarily depend on the incoming solar radiation. The Earth absorbs approximately 3.85 million EJ of solar energy per year [2].

2 Previous Research

The inspiration of combining photovoltaic and solar thermal collectors (PV/T collectors) to provide electrical and heat energy is not new, however it is an area that has received only little interest [3]. With concern growing over energy sources and their usage, PV/Ts have become an area which is receiving much more attention. Research in this field was carried out in the middle of 1970s to early 1980s.

The first inventor of flat-plate PV/T liquid system, Wolf [4] analyzed the performance of the combination of heating and photovoltaic power systems for residences. He concluded that the system was technically feasible and cost effective. Bergene at al. [5] perform theoretical examination of a flat plate solar collector model that integrated with solar cells. They developed a series of algorithms for making quantitative predictions for both the electrical and thermal efficiency of a PVT system. They concluded that a system with combination of both components produced approximately about 60-80% efficiency. Huang et al. [6] have developed PV/T system using a polycrystalline solar PV panel, adopted to be combined with a collector plate. The collector plate is directly attached with the commercial PV panel using the thermal grease, for better contact. Underneath the collector, a PU thermal insulation layer is attached using a fixing frame. The collector was designed using the corrugated plate made of polycarbonate material. The water was flowed into the flow channel of the corrugated plate structure.

Zondag et al. [7] reviewed various concepts of combined PV-thermal collector technologies by introducing and evaluating nine different designs, ranging from the complicated to the simpler one, in order to investigate the maximum yield. They concluded that the design of the channel below the transparent PV, with 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. [8] and conclude that the best design configuration is the spiral flow design with thermal efficiency of 50.12% and cell efficiency of 11.98%. Hybrid Photovoltaic Thermal Collector (PVT) for the Production of Hot Water and Electricity has been studied by Ibrahim et al. [9] and conclude that the Special design had best design configuration with total efficiency of 63.55%.

Ibrahim et al. [10] studied the thermal theoretical study on PV/T water based collectors, Simulations have been performed to investigate the effect of various mass flow rates against the thermal, electrical and combination of both photovoltaic thermal efficiencies of three absorber collectors design.

The simulation results shows that the Single flow absorber collector generates combined PV/T efficiency of 64% with electrical efficiency of 11%

3 PVT Collector Analysis

The performance of PVT collectors can be depicted by the combination of efficiency expression [11]. It comprised of the thermal efficiency η_{th} and the electrical efficiency η_{el}. These efficiencies usually include the ratio of the useful thermal gain and electrical gain of the system to the incident solar irradiation on the collector's gap within a specific time or period.

The total of the efficiencies, which is known as total efficiency $\eta_{overall}$ is used to evaluate the overall performance of the system:

$$\eta_{\mathrm{overall}} = \eta_{\mathrm{th}} + \eta_{pv}$$

The thermal performance of the PVT is affected by many system design parameters and operating conditions. In this paper, the system is analyzed with various configurations of solar radiation, ambient temperature, and flow rate conditions. Based on this assumption, the thermal performance η_{th} of the PVT unit is evaluated for its thermal and photovoltaic performance, as such, the derivation of the efficiency parameters based on the Hottel-Whillier equations [12] were used. The thermal efficiency (η_{th}) of the conventional flat plate solar collector is calculated using the formula below:

$$\eta_{\mathrm{th}} = \frac{Q_u}{G}$$

Where Q_u= actual useful collected heat gain (W/m^2) and G= measurement of incoming solar-irradiation on the collector surface (W/m^2). Under these conditions, the useful collected heat gain (Q_u) is given by:

$$Q_{\mathrm{u}} = \dot{m} C_p (T_o - T_i)$$

Where $\dot{m}$ = mass flow rate (Kg/s), C_p= specific heat of the collector cooling medium (J/kg K), T_o = fluid outlet temperature (K) and T_i = fluid inlet temperature (K).

The difference between the absorber solar radiation and thermal heat losses is identified by Hottel-Whillier equations [12]:

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

S can be identified as $S = (\tau\alpha) G_T$

Where A_c = function of the collector area (m^2), F_R = heat removal efficiency factor, S = absorbed solar energy (W/m^2), U_L = overall collector heat loss coefficient (W/m^2 K), T_i = fluid inlet temperature (K), T_a = ambient temperature (K), $(\tau\alpha)_{pv}$ = PV thermal efficiency and G_T = solar radiation at (irradiation 800 W/m^2, wind velocity 1 m/s, ambient temperature at 26 ºC).

The heat removal efficiency factor (F_R) can be calculated as below, where F' is the corrected fin efficiency.

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

The corrected fin efficiency (F') is calculated using:

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

Where D = hydraulic diameter of the tube (m), W = tube spacing (m), F = fin efficiency factor, C_b= conductance of the bond between the fin and square tube (W/m^2 K) and h_{fi} = heat transfer coefficient of fluid (W/m^2 K).

The fin efficiency factor F is then be calculated as:

$$\mathrm{F} = \frac{\tanh\left[\mathrm{M}\left(\frac{\mathrm{W - D}}{2} \right) \right]}{\mathrm{M}\left(\frac{\mathrm{W - D}}{2} \right)} \text{ Where } \mathrm{M} = \sqrt{\frac{U_L}{(K_{abs} L_{abs}) + (K_{pv} + L_{pv})}}$$

Where K_{abs} = absorber thermal conductivity (W/m^2 K), L_{abs} = absorber thickness (m), K_{pv} = photovoltaic thermal conductivity (W/m^2 K) and L_{pv} = PV collector thickness.

From this equation, it is then possible to calculate the useful heat gain of the solar collector by rearranging the equation, the thermal efficiency of the collector can be expressed as [13]:

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

For temperature-dependent electrical efficiency of the PV panel, (η_{el}) the expression is given as below [14]:

$$\eta_{el} = \eta_{\mathrm{r}} \left(1 - \gamma (T_{pm} - T_r) \right)$$

Where η_{el} = electrical efficiency, η_r reference efficiency of PV panel (η_r= 0.12), β = temperature coefficient (ºC 0.0045ºC-1), T_{pm} = temperature of the solar cells (K), T_r = the reference temperature. The analytical characteristics of the PVT collector are presented in Table 1.

Table 1. Characteristics PVT collector.

Ambient temperature	T_a	297 K
Inlet fluid temperature	T_i	297 K
Collector width	b	0.505 m
Tube diameter	D	0.025 m
Tube spacing	W	0.02 m
Collector parameter	P	3.3 m
Collector area	Ac	0.674 m²
Number of glass cover	N	1
Emittance of glass	εg	0.88
Emittance of plate	εp	0.95
Tilt (slope)	º	14
Fluid flow rate	m_{dot}	0.045 kg/s
Fluid thermal conductivity	k_{fluid}	0.613
Back insulation conductivity	Cp	4180
Specific heat	k_b	0.045 W/mºK
Back insulation thickness	L_b	0.05 m
Insulation conductivity	k_e	0.045 W/mºK
Edge insulation thickness	L_e	0.025 m
Absorber conductivity	k_{abs}	51 W/mºK
Absorber thickness	L_{abs}	0.002 m
Fin conductivity	k_f	84 W/mºK
Fin thickness	δ	0.0005 m
Heat transfer coefficient from cell to absorber	h_{ca}	45 W/mºK
Heat transfer inside tube	h_{fi}	333 W/mºK
Transmittance	τ	0.88
Absorptance	α	0.95

4 Design Configurations of the Absorber Collectors

As the PV cells in PV module are exposed the sun, it generates electricity and at the same time absorbed the heat causing the absorber to increase its temperature. During this time, the water fluid passing inside the absorber tubes is heated due to the contact underneath the PV module. The water is then flows along the absorber through a manifold and pipes before finally fed to a water tank. The absorbers are equipped with inlet and outlet at opposite ends of the hollow tubes. This will ensure that the trapped water in the absorber can be releases. The system is considered to be a closed loop system, where the fresh and cooler water enters the hollow tubes is heated continuously. In this study, use the rectangular tube absorber design under the PV as shown in Fig. 1.

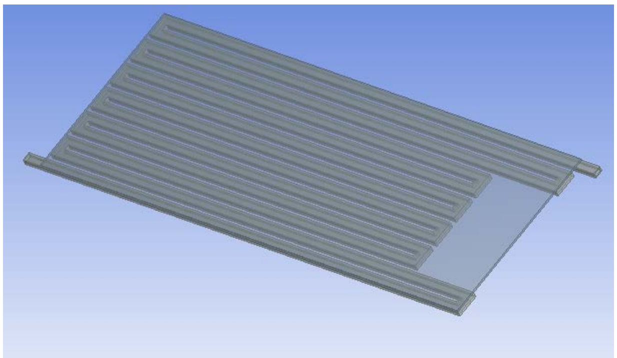

Fig.1 The Rectangular Tube Absorber Design.

5 Results and Discussion

In this simulation, the specific operation condition is set from 10:00 hours till 17:00 hours. Data for the ambient temperatures were collected from local weather station shows that at 10:00 hours, the ambient temperature is at 28.60 °C and 33:55 °C at 17:00 hours with the peak at 37:50 °C at 14:50 hours. Fig. 2 and Fig. 3 show the hourly average variation of solar radiation and ambient temperature. As shown in Fig. 2 and Fig. 3 the variation of PV temperature versus the time. The PV temperature and outlet temperature increases with the time and solar radiation. As the solar radiation decreases the rate of increasing in temperature of PV and outlet temperature also decreases. A maximum predicted PV temperature of 54.40 °C and 48.80 °C for outlet temperature are obtained.

Referring to Fig. 2 and Fig. 3, the daily mean values of ambient temperature, outlet temperature and solar radiation varied approximately (27.60-37) °C, (29-48.50) °C, and (406.50 – 889.23) W/m^2 respectively. The PV, thermal and PVT energy varied continuously with increasing solar radiation and time. The results, the PV, thermal and PVT energy varied (31-60.5) W, (229–455) W, (260-515.5) W respectively at mass flow rate 0.045 Kg/s.

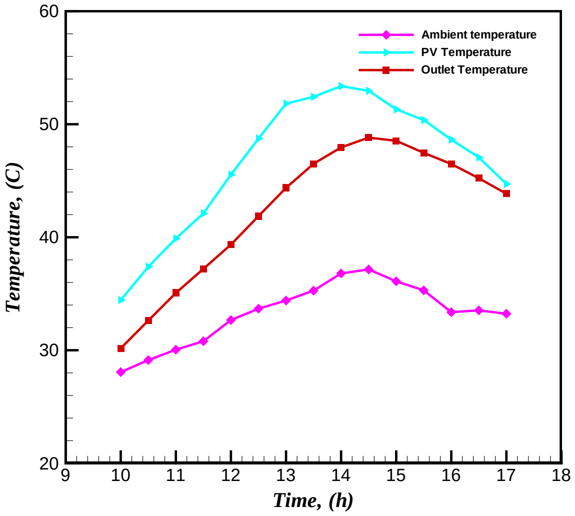

Fig.2 Variation of temperatures versus the time.

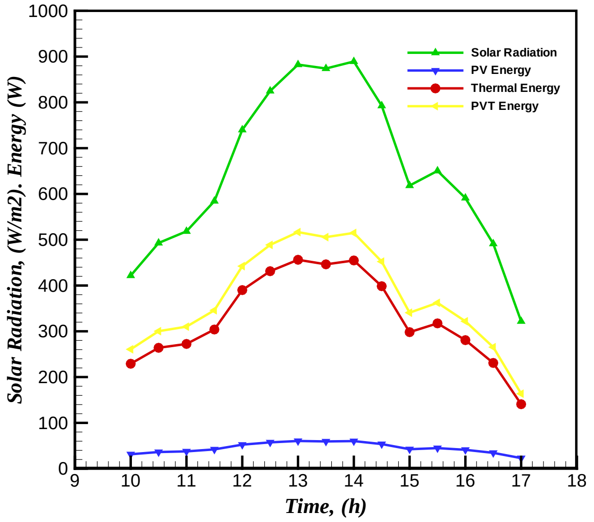

Fig. 3 Average Hourly Radiation and Performances with Time.

In determining efficiency of collector, the effectiveness can be represented by an efficiency curve, which indicates the efficiency versus the reduced temperature parameters or $(T_i-T_a)/S$. Thermal and PVT efficiencies as function of ratio of $(T_i-T_a)/S$ are shown in Fig. 4, the efficiency curve decrease as the $(T_i-T_a)/S$ increase.

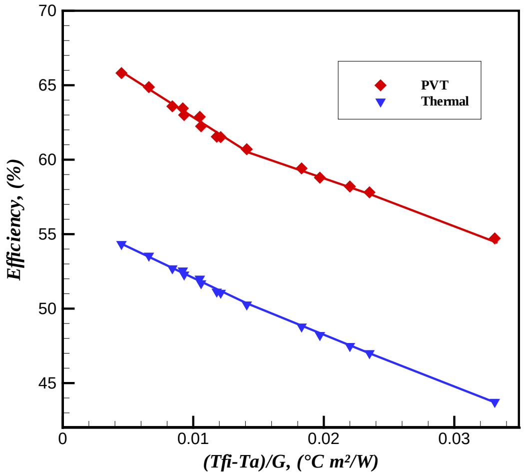

Fig. 4 Variation of PVT and Thermal efficiencies as function of the ratio $(T_i\text{-}T_a)/S$.

As shown in Fig. 5 the PV efficiency decreases with increasing the PV temperature. The PV efficiency is between (10.35-11.5)%. Thermal and PVT efficiencies as function of ratio of (Ti-Ta)/S are shown in Fig. 4. The efficiency curve decreases as the (Ti-Ta)/S increase. The thermal and PVT energy efficiencies are ranging from (43.7-54.3) % and (54.7-65.8) % respectively, as shown in Fig. 4.

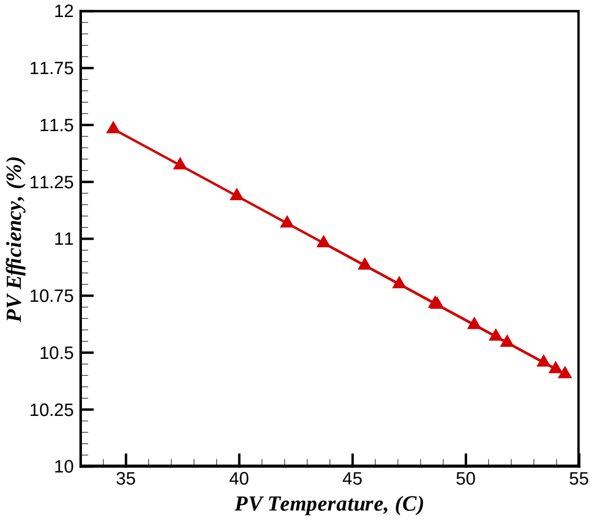

Fig. 5 PV Efficiency as a Function of PV Temperature.

Fig. 6 shows the hourly variation of PV, thermal, PVT and Primary energy saving efficiencies with rectangular tube design at the mass flow rate of 0.045 kg/s. The collector were produced PVT efficiency of (54.7-65.8) % with (10.4-11.4) % PV efficiency and of (44.3-54.4) % thermal efficiency, also it is produced primary energy saving efficiency from (72-84.5) %.

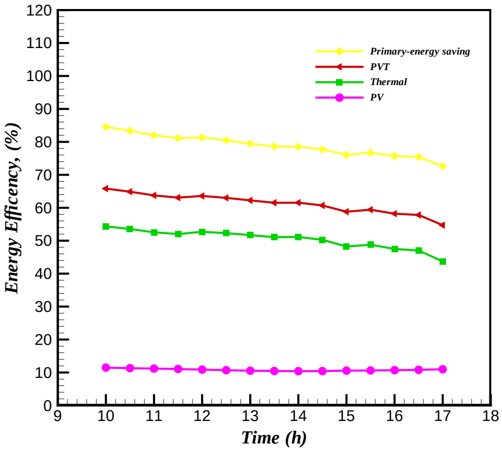

Fig. 6 Changes of Efficiencies Over Time at Mass Flow Rate 0.045 kg/s.

6 Conclusion

Solar cells generate more electricity when receive more solar radiation but the efficiency drops when temperature of solar cells increase. Hybrid photovoltaic and thermal collector can solve the problem. Photovoltaic thermal collector with Rectangular tube shows better performance in cooling, electrical and thermal efficiency. Results indicate that the electrical and thermal production of a PV/T hybrid system increases with decreasing temperature of ambient. At mass flow rate of 0.045 kg/s, electric efficiency can archive 11.4 % and PV/T efficiency of 65.8%. It is recommended for PV/T system to further improve its efficiency by optimizing the contact surfaces between the solar panel (photovoltaic module) and the tubes underneath.

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