Thermal theoretical study on PV/T water based collectors

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Abstract: – 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 first collector, known as Spiral flow absorber collector, the second collector, known as Web absorber collector and the third collector, known as Oscillatory absorber collector. In this simulation, it is assumed that the absorber collectors are attached underneath the flat plate single glazing sheet of polycrystalline silicon photovoltaic module and water has been used as a heat transfer medium in absorber collectors respectively. The simulation results shows that the Single flow absorber collector generates combined PV/T efficiency of 64% with electrical efficiency of 11%, the Web absorber collector generates combined PV/T efficiency of 44% with electrical efficiency of 5.9% and the Oscillatory absorber collector generates combined PV/T efficiency of 40% with electrical efficiency of 5.4%. The mass flow rate is set at 0.011 kg/s for all absorber collectors. 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.

Keywords: – Absorber collectors, electrical efficiency, Photovoltaic/Thermal (PV/T), thermal efficiency.

1 Introduction
Many researches towards the solar energy occur all over the world due to the concern of global crisis on oil and gas prices. According to some experts, oil has already started to peak [1]. Gas and coal reserves are bigger than oil, will tend to be progressively replaced by the former, which should attenuate a price explosion. Nevertheless this process will push energy prices higher, until sustainable sources replace dependency on fossil fuels as major source of energy [2]. The sustainable energy such as solar energy has been identified as one of the promising source of energy to replace the dependency on fossil fuels.

The technology of solar energy or synonym to be known as photovoltaic technology (PV) has many advantages comparing to others energy [3]. It works on noiseless environment; do not produce any unwanted waste such as radioactive materials etc, highly credibility system with life span expectation is between 20 to 30 years and very low maintenance system. Hybrid photovoltaic thermal system in the other hand is the continuity of the photovoltaic system. The usage of the solar energy in general can be divided into two divisions; the photovoltaic technology that converts the solar energy into electricity, (which derived from solar cell technology) and thermal solar technology that convert the solar energy into heat, (which derived from the absorber plate). The heat can be either in the form of hot air or water [4] [5] [6]. There are many methods of producing the photovoltaic thermal collectors cite from the previous and prestige researchers all over the world. The most common design types can be either a flat-plate collectors or concentrating types have been designed depending on the types of working medium used such as water, air or combination between water and air.
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 [7]. 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 [8] 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. In his experiment, the Hottel-Whillier model [9] is used to analyze the combination of photovoltaic and thermal flat plate collectors with the traditional hot water system and PV panel to minimize the usage of the installation area. It is proven that by combining the system, the installation area produce more energy per unit surface area than one PV panel and one thermal system [10]. Zondag et al. [4] 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. Bergene at al. [11] 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 PV/T system. They concluded that a system with combination of both components produced approximately about 60-80% efficiency. Huang et al. [12] 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 is directly attached with the commercial PV panel to minimize the usage of the installation area. It is proven that by combining the system, the installation area produce more energy per unit surface area than one PV panel and one thermal system [10]. Zondag et al. [4] 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. Bergene at al. [11] 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 PV/T system. They concluded that a system with combination of both components produced approximately about 60-80% efficiency. Huang et al. [12] 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. The objective of this paper is to investigate the influence of various mass flow rates against the efficiency of three absorber collectors. The result of this paper will provide useful information about the influence of mass flow rates to the efficiency of absorber collectors design.

2 Research Method

The performance of PV/T collectors can be depicted by the combination of efficiency expression [13]. It comprised of the thermal efficiency $\eta_{th}$ and the electrical efficiency $\eta_e$. 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 analytical parameters of the PV/T collector are presented in Table 1. The total of the efficiencies, which is known as total efficiency $\eta_o$ is used to evaluate the overall performance of the system:

$$\eta_o = \eta_{thermal} + \eta_{electrical}$$

The thermal performance of the PV/T is affected by many system design parameters and operating conditions. In this simulation, the system is analyzed with various configurations of solar radiation, ambient temperature, and flow rate conditions. The collector is assumed to be represented as a flat plate thermal collector with single glazing sheet. Based on this assumption, the thermal performance $\eta_{th}$ of the PV/T unit is evaluated for its thermal and photovoltaic performance, as such, the derivation of the efficiency parameters based on the Hottel-Whillier equations [9] were used. The thermal efficiency ($\eta_{th}$) of the conventional flat plate solar collector is calculated using the formula below:

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

Where $Q_u$ is 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:

$$Q_u = mC_p(T_o - T_i)$$

Where $m$ = 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 [9]:

$$Q_u = A_\varepsilon F_R \left[ S - U_r (T_o - T_i) \right]$$

Where $A_\varepsilon$ = 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), $\tau_{PV}$ = PV thermal efficiency and $G_T$ = solar radiation at NOCT (irradiation level 800 W/m$^2$, wind velocity 1 m/s, ambient temperature at 26 ºC taken every 30 minutes)

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

$$F_R = \frac{m \cdot C_p}{A_L \cdot U_L} \left[ 1 - \exp \left( -\frac{A_L \cdot U_L \cdot F'}{m \cdot C_p} \right) \right]$$

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

$$F' = \left[ \frac{1}{U_L} \right] \left[ \frac{d_a + (W - d_a) \cdot F}{U_L} \right] + \frac{1}{C_b} + \frac{1}{2(a + b) \cdot h_f}$$

$$= \left[ \frac{1}{U_L} \right] \left[ \frac{d_a + (W - d_a) \cdot F}{U_L} \right] + \frac{1}{C_b} + \frac{1}{2(a + b) \cdot h_f}$$

Where $d_a$ = 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 $h_f$ = heat transfer coefficient of fluid (W/m$^2$ K)

The fin efficiency factor $F$ is then be calculated as:

$$F = \frac{\tanh \left( m \cdot \frac{W - d_a}{2} \right)}{m} \cdot \frac{U_L}{\sqrt{K_{abs} \cdot L_{abs} + K_{PV} \cdot L_{PV}}}, \text{ where } m = \left( \frac{U_L}{K_{abs} \cdot L_{abs} + K_{PV} \cdot L_{PV}} \right)$$

Where $m$ = mass flow rate (Kg/s), $K_{abs}$ = absorber thermal conductivity (W/m2 K), $L_{abs}$ = absorber thickness (m), $K_{PV}$ = photovoltaic thermal conductivity (W/m2 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 [14]:

$$\eta_{th} = F_R \left( \tau \alpha \right)_{PV} - F_R U_L \frac{T_r - T_i}{G_T}$$

For temperature-dependent electrical efficiency of the PV panel, ($\eta_e$) the expression is given as below [15]:

$$\eta_e = \eta_r \left[ 1 - \beta (T_c - T_r) \right]$$

Where $\eta_e$ = electrical efficiency, $\eta_r$ = reference efficiency of PV panel ($\eta_r = 0.12$), $\beta$ = temperature coefficient (ºC 0.0045ºC$^{-1}$), $T_c$ = temperature of the solar cells (K), $T_r$ = the reference temperature and $T_r$ = the reference temperature.

### 3 Simulation Consideration

In order to obtain the best results, proper design factors need to be considered. The dual requirement of good thermal conduction and good electrical insulation between the solar cells and absorber collector need to be considered [16]. As seen in Figure 1 to 3, the absorber collectors conceptual design have been presented using Solidworks software, assumed to be made from rectangular hollow tubes of stainless steel material with dimension of 12.7mm x 12.7mm. The tubes are assumed to be connected using a welding method. Each collector has been designed with a single unilateral channel for the water to flow in it with the size of 815mm x 628mm before it is assembled underneath the PV panel.

![Fig. 1. Spiral Flow Design](image1)

![Fig. 2. Web Flow Design](image2)

![Fig. 3. Oscillatory Flow Design](image3)

Table 1 shows the parameters of the absorber collectors design. The absorbers in the form of round and rectangular hollow tubes are attached...
closely underneath the PV module with metallic bonded; this will ensure a zero gap or no gap between the tubes and the module, in which heat can be transferred.

Table 1. Absorber collector simulation parameters

<table>
<thead>
<tr>
<th>Description</th>
<th>Symbol</th>
<th>Value</th>
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<tr>
<td>Ambient temperature</td>
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<tr>
<td>Inlet fluid temperature</td>
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<td>293</td>
</tr>
<tr>
<td>Tube length</td>
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<td>Collector width</td>
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<td>Tube diameter</td>
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<tr>
<td>Number of glass cover</td>
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<td>Emittance of glass</td>
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</tr>
<tr>
<td>Emittance of plate</td>
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<td>Tilt (slope)</td>
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<tr>
<td>Fluid flow rate</td>
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<td>Fluid thermal conductivity</td>
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<td>Back insulation conductivity</td>
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<tr>
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<td>Insulation conductivity</td>
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<tr>
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<tr>
<td>Absorptance</td>
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</table>

4 Results Of The Simulations

In this simulation using excel software, it is assumed that the specific operation condition is set from 06.00 hours till 20.00 hours. The data for the ambient temperature were collected from local weather station shows that at 06.00 hours, the ambient temperature is at 21.49°C and 26.49 °C at 20.00 with the peak at 36.11 °C at 14.00 hours. The average solar radiation level during the simulation period was 883.11 W/m² respectively. The result of this simulation as seen in Figure 4a and 4b shows the electrical and thermal efficiency versus the surface temperature and mass flow rate for Spiral absorber collector. In this simulation, the data shows that the surface temperature at 55°C and mass flow rate of 0.011 kg/s, the absorber collector generates combined PV/T efficiency of 64%, with electrical efficiency of 11%. Figure 5a and 5b shows the electrical and thermal efficiency versus the surface temperature and mass flow rate for Web absorber collector. The data shows that surface temperature at 60°C and mass flow rate of 0.011 kg/s, the absorber collector generates combined PV/T efficiency of 44%, with electrical efficiency of 5.9%. Figure 6a and 6b shows the electrical and thermal efficiency versus the surface temperature and mass flow rate for Oscillatory absorber collector. In this simulation, the data shows that the surface temperature at 68°C and mass flow rate of 0.011 kg/s, the absorber collector generates combined PV/T efficiency of 40%, with electrical efficiency of 5.4%. The results show that when mass flow rate increases, the surface temperature decrease and at the same time the efficiencies for electrical and thermal increase. The surface temperature of each individual absorber collector as in Figure 4a and 4b, 5a and 5b and 6a and 6b are varied. It is noted that the design of the collector versus the area covered plays an important aspect in designing the absorber collector. The more area covered to surface of the PV, will cooler the surface of the PV; generates higher efficiency to electrical and thermal efficiency to the system. Figure 6, 7 and 8 shows the dependence of electrical, thermal and combined PV/T efficiency on the mass flow rates of the Spiral flow, Web flow and Oscillatory absorber collector respectively. The efficiencies approach steady state values as the mass flow rate increases. In this simulation, it proved that the collector absorber reached the steady state at a threshold mass flow rate of 0.011 kg/s[17].
Fig. 4a. Electrical efficiency and surface temperature versus mass flow rate for Spiral flow absorber collector

Fig. 4b. Thermal efficiency and surface temperature versus mass flow rate for Spiral flow absorber collector

Fig. 5a. Electrical efficiency and surface temperature versus mass flow rate for Web flow absorber collector

Fig. 5b. Thermal efficiency and surface temperature versus mass flow rate for Web flow absorber collector

Fig. 6a. Electrical efficiency and surface temperature versus mass flow rate for Oscillatory flow absorber collector

Fig. 6b. Thermal efficiency and surface temperature versus mass flow rate for Oscillatory flow absorber collector
Fig. 6. Combined PV/T efficiency versus various mass flow rates for Spiral flow absorber collector.

Fig. 7. Combined PV/T efficiency versus various mass flow rates for Web flow absorber collector.

Fig. 8. Combined PV/T efficiency versus various mass flow rates for Oscillatory absorber collector.

Fig. 9: I-V curve for Bare plate solar panel, Web, Oscillatory and Spiral flow absorber collector.

The behaviour of the I-V curve for the collectors is shown in Figure 9 along with the bare plate solar panel for comparison purposes. This can be explained based on the observations as in Figure 6, 7 and 8. The open circuit voltage ($V_{oc}$), short circuit current ($I_{sc}$) of the Spiral flow absorber collector is the highest amongst other collectors due to the low surface temperature of the panel.

From the observation, the result shows that the Spiral flow absorber collector has the power maximum of 25.35W, the Oscillatory absorber collector has the power maximum of 17.64W, and Web absorber collector has the power maximum of 15.86W. The three collectors are compared to a bare plate solar panel that giving a power maximum of 20.66W.

5 Conclusion

The photovoltaic solar collector comprises of a combined photovoltaic module (PV) and an absorber collector for building integrated photovoltaic thermal (PV/T) application, have been simulated and investigated. The optimum operating temperature of the photovoltaic module and efficiency conversion have been obtained, determined and maintained.

Results indicated that for Spiral flow absorber collector, at temperature of 55°C (Panel surface temperature), mass flow rate at 0.011 kg/s; the absorber collector generates combined PV/T efficiency of 64%, with 11% of electrical efficiency. For Web absorber collector, at temperature of 60°C (Panel surface temperature), mass flow rate of 0.011 kg/s, the absorber collector generates combined
PV/T efficiency of 44%, with electrical efficiency of 5.9%. For Oscillatory absorber collector, at temperature of 68ºC (Panel surface temperature), mass flow rate of 0.011 kg/s, the absorber collector generates combined PV/T efficiency of 40%, with electrical efficiency of 5.4%.

As a conclusion, from this simulation, it is proven that Spiral flow absorber collector is the best design to fulfill the aspect of integration between absorber collector and PV panel. 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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