Simulation of Amorphous and Crystalline Silicon Based Photovoltaic Thermal System

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Abstract: - A system with PVT collectors generates electricity which can utilize it directly, store it in batteries and send it to electrical grid. This system produces thermal energy that can be employed for process heat, hot shower and tap water, solar cooling and desalination. Building integrated photovoltaic thermal systems (BIPV/T) is a new concept that received much more attention. This work shows the results of performance simulation study of a-Si and c-Si photovoltaic/thermal (PVT) solar collector in tropical climate such as Malaysia. The results show that at solar radiation between 700-900 W/m², ambient temperature between 23-34°C and fluid flow rate of 0.03 kg/s, the highest thermal and electrical efficiency of the PV/T (a-Si) was 72% and 5%, respectively, the highest thermal efficiency of (c-Si) was 51% and cell efficiency was 11.6%.

Key-Words: - Photovoltaic thermal (PVT), Electricity, Thermal efficiency, Solar Energy, Water Heating, a-Si.

1 Introduction

The advent of the energy crisis in the early 1970s led to the concept of hybrid PV/T systems became much more favorable research area. The hybrid photovoltaic/thermal (PV/T) systems refer to the integration of a PV and a conventional solar thermal collector in a single piece of equipment [1] which can be used effectively for the conversion of the absorbed solar radiation into electricity and heat, therefore increasing their total energy output [2]. The first research of water based PV/T systems were reported in the middle of 1970s to early 1980s where the performance of integration of photovoltaic and thermal system for hot water production based on Hottel-Whillier model [3] had been analyzed and it was observed that the system is economic and feasible [4]. The main concept of photovoltaic thermal collector using water or air as the working fluid was proposed by Kern and Russell in 1978 [5]. Florschuetz performed the theoretical analysis of a PV/T collector through an improved Hottel–Whillier model [6]. A comparative experimental study in (PV/T) collectors with liquid and air as the heat removal fluid (working fluid) was made by Hendrie and Raghuraman (1980) [7]. The heat transfer at the air gap behind the photovoltaic panels was studied by Moshfegh and Sandberg [8]. Later, a commercial polycrystalline PV module was used for making a PV/T collector as compared to a conventional solar water heater and to demonstrate the idea of an integrated photovoltaic and thermal solar system (IPVTS). The primary-energy saving efficiency of this IPVTS exceeded 0.60. This was higher than for a pure solar hot water heater or a pure PV system. The characteristic daily efficiency reached 0.38 which was about 76% of the value for a conventional solar hot water heater using glazed collectors [9].

Research of hybrid PV/T solar systems for domestic hot water and electricity production continued and in recent years, one combined system was designed [10]. In this work, both passive (thermosyphonic) and active systems were considered. The results of this study showed that a substantial amount of thermal and electrical energy was produced especially when both hot water and electricity was required, particularly in applications where low temperature water like hot water production for domestic use, was required.

A PV/T water heating system with natural circulation was proposed [11,12], the whole PV/T assembly was placed in a flat-box Al-alloy frame and the water heating system comprises of one collector, one water tank, the valves and pipes. The results of experimental works revealed that by
incrementing the hot-water load per unit heat-collecting area to 80 kg/m², the daily electrical efficiency, the characteristic daily thermal efficiency, the characteristic daily total efficiency and the characteristic daily primary-energy saving was about 10.15%, more than 45%, above 52% and up to 65%, for this system with a PV cell covering factor of 0.63 and front-glazing transmissivity of 0.83, respectively. The simulation results showed that the overall performance system increased with the higher the covering factor and the glazing transmissivity. This system had been tested some years ago [13] and the results showed that a high hot water temperature in the collector system can be achieved.

PV/T dual systems were designed [14] and in their collectors both water and air heat exchangers (WHE and AHE) were together in the same device and there were three main modes of arrangements. In mode A, water heat extraction was in contact with PV rear surface. In mode B, air heat extraction acted as the additional element of WHE and played the role of the thin metallic sheet (TMS) in the air channel. Mode C as the WHE was simply placed on the opposite air channel wall, this system was easier in construction than the other two arrangements. The results of experimental works indicated that, mode A was the most effective combination for the heat extraction operation among the three tested system design modes. With modification of systems, satisfactory thermal efficiency for both water and air heat extraction systems were obtained.

A solar water heater system using a glass to glass PV/T module developed [15]. It was concluded that this system was a self sustainable system and could be installed at remote areas for fulfillment of hot water requirements and electrical energy production. It was added that absorber collector which covered partially with PV module gave better thermal and average cell efficiency compare to studies have been done by earlier researchers.

Ibrahim et.al [16] have designed investigated and compared seven new design configurations of absorber collectors. Simulations were performed to determine the best absorber design that gives the highest efficiency (total efficiency). Based on these simulations, spiral flow design proved to be the best design with the highest thermal efficiency of 50.12% and corresponding cell efficiency of 11.98%.

The design of a novel building integrated photovoltaic/thermal (BIPVT) solar collector was theoretically analyzed through the use of a modified Hottel–Whillier model and was validated with experimental data from testing on a prototype BIPVT collector [17]. The results showed that key design parameters such as the fin efficiency, the thermal conductivity between the PV cells and their supporting structure, and the lamination method had a significant influence on both the electrical and thermal efficiency of the BIPVT.

The theoretical analysis of PV/T systems for domestic heating and cooling was reported by [18]. By using the F-chart and F-chart cooling methods, it concluded that the thermal energy produced by PV/T systems may cover remarkable part of the domestic heating and cooling load. The geographical region has important affect on the percentage of the solar coverage of the domestic heating and cooling load.

Water hybrid PV/T collectors applied to comisystems of heating systems and domestic hot water proposed [19]. The advantage of the direct solar floor (DSF) was that an additional solar tank was not used due to the fact that solar energy was directly stored in the floor. In this study a direct solar floor application had been considered because of its low operating temperature level which was 35°C maximum and it was likeable for a PV electricity production.

An experimental study of BIPVT system was conducted [20]. This system served as a water pre-heating system. The experimental results were chosen to study the heat gains (in accordance with space cooling loads) across the PV/T wall as compared to the reference wall in the peak summer period and the cooling load patterns compared between the PV/T wall and the reference wall in winter. The results showed that the PV/T wall reduces the air-conditioned load and the space thermal loads can be much decreased in summer and winter.

2 PV/T collector

In order to improve the global energy efficiency of PV/T modules by extracting the heat loose using a heat removal fluid; a simple and well designed absorber collector, in which water is heated and the PV module temperature can be reduced to keep electrical efficiency at the sufficient level, simultaneously has been proposed and the absorber built of Aluminum. (Fig.1).
3 Methodology

The useful energy collected of collector is given by:

\[ Q_u = A_c F_R \left[ (\alpha \alpha_n) G_T - U_L (T_i - T_a) \right] \]  \hspace{1cm} (1)

Collector heat removal factor \((F_R)\), is introduced \([21, 22]\):

\[ F_R = \frac{m C_p}{A_c U_L} \left[ 1 - e^{-\frac{A_c U_L F}{m c_r}} \right] \]  \hspace{1cm} (2)

Where the collector efficiency Factor is defined as:

\[ F = \sqrt[1/N_c]{\frac{1}{U_L}} \left[ \frac{1}{w D_h} \right] \]  \hspace{1cm} (3)

The fin efficiency factor \(F\) is given by:

\[ F = \frac{\tan \left[ \frac{m \cdot w - D_h}{2} \right]}{w - D_h} \]  \hspace{1cm} (4)

Then:

\[ m = \frac{U_L}{k_{abs} L_{abs} + K_{pv} L_{pv}} \]  \hspace{1cm} (5)

The collector overall loss coefficient \(U_L\), is the sum of the top, bottom and edge loss coefficients:

The back loss coefficient is calculated by:

\[ U_b = \frac{K_h}{L_h} \]  \hspace{1cm} (6)

The edge loss coefficient, based on the collector area is:

\[ U_e = \frac{(UA)_{edge}}{A_c} \]  \hspace{1cm} (7)

And the top loss coefficient is:

\[ U_t = \frac{T_{pm} (T_{pm} - T_a) e}{N + f} + \frac{1}{h_w} \]  \hspace{1cm} (8)

Useful energy gain by the collector heats the collector fluid, therefore:

\[ Q' = m C_p (T_o - T_i) \]  \hspace{1cm} (9)

Thus,

\[ \frac{Q_u}{A_c} = F_R \left[ (\alpha \alpha_n) G_T - U_L (T_i - T_a) \right] = \frac{m C_p (T_o - T_i)}{A_c} \]  \hspace{1cm} (10)

The collector efficiency defined as:

\[ \frac{Q_u}{G_T} = F_R \left[ (\alpha \alpha_n) - \frac{U_L (T_i - T_o)}{G_T} \right] = \frac{m C_p (T_o - T_i)}{A_c G_T} \]  \hspace{1cm} (11)

Electrical efficiency of the PV module, which is a function of average module temperature, \(\eta_e\) is given by:

\[ \eta_e = \eta_r (1 - \beta (T_c - T)) \]  \hspace{1cm} (12)

Where \(\eta_e = \) electrical efficiency, \(\eta_r = \) reference efficiency of PV panel, \(\beta = \) temperature coefficient , \(T_c = \) temperature of the solar cells (K), and \(T\) = the reference temperature.
4 Results and Discussion

The hourly average variation of solar irradiation and ambient temperature for a typical day in the middle of March for Malaysia shows in Figure 2.

Fig. 2 Average hourly radiation and ambient temperature with time

Fig. 3 shows the variation of water temperatures versus the time for a-silicon and c-silicon PV/T modules. The water temperature steadily increases with time and solar irradiation. As the solar irradiation decreases, the rate of increasing in temperature of water also decreases. A maximum predicted water temperature of 62°C for amorphous and 56°C for crystalline are obtained.

Fig. 3 variation of output water temperature with time

Hence the energy that arrived at the heat absorber plate through the PV cells was reduced due to decreasing of solar radiation; this lowered the heat gain of water at the absorber, therefore the water temperature decreased.

The effect of mass flow rate on the photovoltaic, thermal, and combined photovoltaic thermal efficiencies are shown in Figure 4 for both kinds of cells, the overall efficiency for amorphous silicon varies from 71 to 76 % and the electrical energy output is between 4.84-5.1% at mass flow rates of 0.01 to 0.04 kg/s.

It can be seen that the overall efficiency for crystalline silicon is between 56-62.5% and the cell efficiency changes from 10.9-11.6.

Fig. 4 Efficiencies versus mass flow rate of coolant

From the figure, it can be seen that the efficiency of the collector is strongly dependent on the fluid flow rate for both kinds of cells. It is observed that as the temperature rise, decrease with increasing mass flow rate, the collector thermal efficiency increase due to declining of average temperature of the absorber plate. Thus, increasing the flow rate will increase the heat transfer coefficient between the channel walls and the water, resulting in a lowering of mean photovoltaic cells temperature; this will increase the electrical efficiency of the collector.

As seen in Fig 4 the thermal, cell and overall efficiency is almost stood at constant point or increase very slowly once the flow rate reaches a special point. After this point, further increasing of the mass flow rate shows insignificant and negligible rise of the system efficiencies, therefore, more increasing the mass flow rate just rise the cost and energy consumption. It can be concluded that optimized mass flow rate should be considered for system.

Fig 5a and b show the thermal efficiencies of crystalline and amorphous silicon as a function of water temperature difference for different mass flow rates. The area inside the square presents possible efficiency for temperature difference that will be set in the range of mass flow rate and solar radiation.
Fig. 5a Thermal efficiency of a-silicon as a function of water temperature difference

Fig. 5b Thermal efficiency of c-silicon as a function of water temperature difference

These figures can be used to find the value of the temperature rise and thermal efficiency of the photovoltaic thermal collector if the water mass flow rate and solar intensity is known. In both cases, thermal efficiency decreases linearly with increase of water temperature difference and it goes up with increment of mass flow rate to a special point and increasing of solar irradiance.

5 Conclusion
In order to get more power and heat from PV/T system, it is necessary to cool the PV cell and decrease its temperature, that it is not an easy task in hot and humid climate areas. There is sometimes a lack of an effective cooling strategy of PV/T panels while ambient temperature during day starts to go up. The water based photovoltaic thermal collector systems are practically more desirable and effective than air based systems under meteorological conditions of these climates. There are several ways to make PVT technology more promising with the advent of newly designed and developed thermal absorber.

This paper reports the results of simulation study of an absorber collector and the following conclusions from this study can be summarized as:

- The overall efficiency of this simple design can be much better than that of conventional absorber for both amorphous and crystalline silicon cells. The thermal and electrical efficiency of the PV/T (a-Si) was able to reach 72% and 5%, respectively, the highest thermal efficiency of (c-Si) was 51% and cell efficiency was 11.6%.

- Amorphous silicon performs well regarding heat production under Malaysia’s tropical hot and humid climate, due to favorable, constant, high solar radiation in Malaysia and predominant diffuse nature of solar radiation, but in order to increase the electricity production crystalline silicon modules perform better than PV/T amorphous silicon.

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Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
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<tbody>
<tr>
<td>A_C</td>
<td>surface area of the PV/T collector</td>
</tr>
<tr>
<td>C_p</td>
<td>specific heat of coolant</td>
</tr>
<tr>
<td>d_h</td>
<td>Hydraulic diameter</td>
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<tr>
<td>F</td>
<td>fin efficiency factor</td>
</tr>
<tr>
<td>F_F</td>
<td>collector efficiency Factor</td>
</tr>
<tr>
<td>F_R</td>
<td>collector heat removal factor</td>
</tr>
<tr>
<td>G_T</td>
<td>Solar radiation at NOCT</td>
</tr>
<tr>
<td>h_c</td>
<td>Heat transfer coefficient between cell and absorber</td>
</tr>
<tr>
<td>h_w</td>
<td>Wind heat transfer coefficient</td>
</tr>
<tr>
<td>K_abs</td>
<td>absorption surface thermal conductivity</td>
</tr>
<tr>
<td>K_b</td>
<td>Back insulation thermal conductivity</td>
</tr>
<tr>
<td>K_c</td>
<td>insulation conductivity</td>
</tr>
<tr>
<td>K_T</td>
<td>Monthly clearness index</td>
</tr>
<tr>
<td>L_abs</td>
<td>Thickness of the absorption surface</td>
</tr>
<tr>
<td>L_b</td>
<td>Back insulation thickness</td>
</tr>
<tr>
<td>m</td>
<td>Mass flow rate</td>
</tr>
<tr>
<td>N</td>
<td>Number of glass covers</td>
</tr>
<tr>
<td>Q_U</td>
<td>Useful energy gain</td>
</tr>
<tr>
<td>T_a</td>
<td>Ambient temperature</td>
</tr>
<tr>
<td>T_C</td>
<td>Average module temperature</td>
</tr>
</tbody>
</table>
\( T_i \)  
Inlet fluid temperature

\( T_O \)  
Outlet fluid temperature

\( T_{pm} \)  
Mean plate temperature

\( T_r \)  
Reference temperature

\( U_A \)  
Building overall heat loss coefficient

\( U_b \)  
Bottom loss coefficient

\( U_e \)  
Edge loss coefficient

\( U_L \)  
Overall loss coefficient

\( w \)  
Flat box spacing

\( \varepsilon_g \)  
Emittance of glass

\( \varepsilon_p \)  
Emittance of plate

\( \delta \)  
Stefan–Boltzmann constant

\((\tau \alpha)_n\)  
Transmittance absorptance of PV/T

References:


