AN OVERALL ENERGY AND EXERGY ANALYSIS OF COPPER/ALUMINIUM (Cu/Al) BASE PHOTOVOLTAIC THERMAL (PVT) COLLECTOR

Hoor Fatima
Centre for Energy Studies
Indian Institute of Technology, Delhi,
Hauz Khas, New Delhi 110016, India

G. N. Tiwari
Bag Energy Research Society (BERS)
Mahamana Nagar, Varanasi 221005,
UP, India

Abstract—In this paper, an electrical performance of glass, tedar (Te), copper/aluminium (Cu/Al) base PV module have been analyzed. On the basis of its electrical performance, it has been observed that glass base PV modules gives better performance due to low operating temperature, hence the analyses of glass base and copper/aluminium (Cu/Al) base photovoltaic thermal (PVT) collector have been done in terms of electrical efficiency. Effect of mass flow rate on the performance copper/aluminium (Cu/Al) base PVT water collector has also been studied. Based on the numerical computation, it has been found that glass and copper/aluminium (Cu/Al) base PVT gives similar performance at mass flow rate of 0.017 kg/sec. The thermal and exergy efficiency of copper/aluminium (Cu/Al) base PVT collector will be 61.05% and 13.35% considering the climatic conditions of New Delhi. The Cu/Al base PVT water collector produced 785.05kWh of thermal energy and 106.67kWh of exergy annually.

Keywords—Photovoltaic thermal (PVT), Copper base, Exergy, Thermal efficiency

I. INTRODUCTION

With the growing awareness on solar energy utilization amongst users in highly populated developing nations such as India, cost effective efficient solar energy systems are needed to reduce the dependence of fossil fuel reserves. Various researches since two decades have been performed in order to achieve the higher efficiency of the solar energy system by building an efficient solar collector. The search for an efficient solar collector will give rise to photovoltaic thermal (PVT) collectors which converts the solar energy into heat and electricity.

The photovoltaic thermal system has been introduced by Wolff and the analysis has also been performed using the Hottel-Whillier model (Wolff M. (1976), Florschuetz L.W.(1979)). Generally the working fluid used to extract the thermal energy from the PVT module is water, air and Nano fluids. Many researchers have performed the thermal modelling of PVT systems using the air as the mode of operation (Bhargava et al.(1991), Tiwari A and Sodha M.S(2006), Cartmell et al.(2004), Hegazy A.A(2000), Kamthania et al.(2011)) and many have researched using water as working fluid (Tiwari A and Sodha M.S(2006), He et al. (2006), Radziemska E. (2009), Gaur A., Tiwari G.N.(2014)). The two fluids have also been reviewed by Chow T.T.(2010) and he suggested that the PVT air collector is best for the space heating and PVT water collector can be best used for pre heating services. The applications of the hybrid photovoltaic/thermal (PVT) technology is reviewed by Brahim T. and Jemni A.(2017) and he suggested that there is a need of a cost effective and energy efficient PVT systems. To build an effective PVT solar collector the material used in the absorber plays a very important role in order to increase the efficiency of the system. Various substances such as glass, fiber imposed plastic, tedar etc. have been used by the researchers to achieve the higher efficiency. Joshi et al. (2009) have compared the performance of glass to glass and glass to tedar PVT collector and he suggested that the efficiency of glass to glass PVT system is reported higher than that of glass to tedar PVT system. The glass to glass PV panel have been reported with higher overall efficiency than glass to tedar PV panels by Sophien et al.(1996). Jaiganesh and Durawamwani (2013) analyzed the effect of ambient temperature and solar radiation on the glass to glass and glass to tedar PVT panels and the efficiency of glass to glass PV panels are reported to be higher. Glass to glass and glass to back sheet structure has also been compared using bifacial silicon solar cell and glass to glass module is recommended to be used because of its higher efficiency (Singh et al.(2015)). A sheet and tube absorber have been developed which shows the effect of number of glass cover used in the PVT system, the results shows that the thermal efficiency PVT collector increases on increasing the number of glazing while the electrical efficiency decreases due to increased fluid temperature and optical losses (Guarracino et al. (2016)). A 68.4% of the overall efficiency have been achieved with the spiral flow design of the PVT water collector (Fuholi et al. (2014)). A aluminium absorber attached PVT collector has been reported with high output density in comparison to a unit PV module (Fujisawa T. and...
Tani T. (1997). The four types of absorber, namely aluminium with fin, aluminium without fin, tedlar and black painted glazing absorbers have been compared and aluminium with fin produced higher overall efficiency (Ziapour et al. (2014)). A 5% improvement in electrical efficiency with additional 65% of thermal efficiency have been reported with PV panel retrofitted with a thermal absorber (Xu et al. (2015)). Zondag H.A. (2008) reviewed that the high thermal resistance between the different layers of a PV module minimizes heat transfer from the top glass cover to fluid. A high overall efficiency of 87.52% has been achieved with the copper sheet laminated PV integrated to a single water channel (Michael J.J. et al. (2016), Michael J.J. and Selvarasan I. (2017)).

The main objective of this paper is to study the performance of photovoltaic (PV) laminated with glass, tedlar (Te), copper/aluminium (Cu/Al) as a base for the composite climate of New Delhi, India. The comparison of the three bases (glass, Te, Cu/Al) have been done on the basis of their electrical efficiencies. The effect of mass flow rate on energy and exergy of copper/aluminium (Cu/Al) base PVT water collector has been analyzed. The daily energy and exergy of the copper/aluminium (Cu/Al) base PVT water collector has been analyzed. Further, the analysis has been carried out for annual useful overall thermal energy and exergy gain. The analysis have been done for the climatic conditions of New Delhi, India. The motive of this study to achieve higher thermal and electrical gain for the copper/aluminium (Cu/Al) base PVT water collector.

II. SYSTEM DESCRIPTION

Case I: Glass base photovoltaic (PV) module

In this case, solar cell is encapsulated under the two glass covers as shown in Fig. 1(a). No flow of fluid (air/water) has been considered below the photovoltaic module. The electrical gain is observed for the glass to glass semi-transparent PV module.

Case II: Te base photovoltaic (PV) module

In this case, there is no flow of fluid (air/water) has been considered below the photovoltaic collector. PV modules have been made by adhering the tedlar (Te) just below the solar cell as shown in Fig. 1(b).

Case III: Cu/Al base photovoltaic (PV) module

In this case, there is no flow of fluid (air/water) has been considered below the photovoltaic collector. PV modules have been made by adhering the copper/aluminium (Cu/Al) sheet just below the solar cell as shown in Fig. 1(c).

Case IV: Cu/Al base photovoltaic thermal water (PVT) collector

In this case, water has been chosen as a working fluid in the copper/aluminium (Cu/Al) base PVT collector as shown in Fig. 1(d). In the proposed PVT collector glass has been used at the top to restrict the long wave radiation and to get maximum efficiency. The solar radiation incident on the collector passes through the glass cover and from the non-packing area of the solar cell. The solar radiation is then absorbed by the copper/aluminium (Cu/Al) plate. Due to high thermal conductivity of the copper (401 W/mK) and aluminium (207 W/mK) which much higher than that of glass (0.816 W/mK) and tedlar (0.033 W/mK), more heat is transferred from the back of the solar cell to the riser tubes by reducing the thermal resistance.

The thermal circuit diagram corresponding to Case IV have been shown in Fig. 2 and the design parameter of the proposed Cu/Al base PVT water collector has been given in Table. 1.
III. THERMAL MODELLING

The energy balance equations have been written for each component of the copper/aluminium (Cu/Al) base PVT collector using following assumptions.

1. The glass to copper/aluminium (Cu/Al) PVT system is in quasi-steady state
2. There are negligible ohmic losses
3. The heat capacity of the glass, copper materials and insulation of PVT collectors is neglected
4. Only one dimensional heat flow is considered
5. There is no stratification in water temperature in the insulated tank

The energy balance equation for all the three cases following (Tiwari A. and Sodha M.S. (2006), Joshi et al. (2009)) have been given below:

**Case I: Glass base photovoltaic (PV) module**

\[ \alpha \tau_g \beta(t) \frac{d}{dt} \left( T_{wi} - T_a \right) = \frac{1}{U_{Lm,water}} \left( \alpha \tau_g \beta(t) I(t) \right) \]

**Case II: Tedlar base photovoltaic (PV) module**

\[ \alpha \tau_g \beta(t) \frac{d}{dt} \left( T_{wi} - T_a \right) = \frac{1}{U_{Lm,water}} \left( \alpha \tau_g \beta(t) I(t) \right) \]

**Case III: Cu/Al base photovoltaic (PV) module**

\[ \alpha \tau_g \beta(t) \frac{d}{dt} \left( T_{wi} - T_a \right) = \frac{1}{U_{Lm,water}} \left( \alpha \tau_g \beta(t) I(t) \right) \]
\[ T_{\text{col}} = \frac{(\alpha r)_{\text{solar}} + (U_{\text{loss}} \times T_a)}{U_{\text{eff}}} \]  

where \( \alpha r \) is the rate of solar energy achieved by the solar cell after transmission, \( U_{\text{loss}}(T_{\text{col}} - T_a)Wdx \) and \( U_{\text{loss}}(T_{\text{col}} - T_a)Wdx \) are the rate of heat loss from the solar cell to ambient for the case of copper/aluminium (Cu/Al) as a base, \( U_{\text{loss}}(T_{\text{col}} - T_a)Wdx \) and \( U_{\text{loss}}(T_{\text{col}} - T_a)Wdx \) are the rate of heat transfer between cell to absorbing copper/aluminium (Cu/Al) plate. \( \eta \tau \beta \) is the electrical energy obtained from the solar cell.

**Case IV: Cu/Al base photovoltaic thermal (PVT) water collector**

**For PV module**

\[ \alpha r \tau \beta I(t)Wdx = U_{\text{loss}}(T_{\text{col}} - T_a)Wdx + U_{\text{loss}}(T_{\text{col}} - T_a)Wdx + \eta \tau \beta \]  

where \[ \eta \tau \beta \] is the rate of useful thermal energy available at the end of copper/aluminium (Cu/Al) base water collector.

**Energy and Exergy calculations**

The expression for the instantaneous thermal efficiency can be given as

\[ \eta_i = \frac{\dot{Q}_u}{A_i I(t)} \]  

An expression for electrical efficiency of a PV module can be calculated as

\[ \eta_e = \eta_i [1 - 0.0045(T_e - T_0)] \]

The rate of useful thermal energy can be evaluated from

\[ \dot{E}_{\text{thermal}} = \eta \dot{E}_{\text{thermal}} = A_m \times \eta_m \times I(t) \]

The rate of useful thermal exergy can be obtained as

\[ \dot{E}_{\text{exergy}} = m_f c_f (T_{fo} - T_f) \]

The useful electrical gain can be evaluated as

\[ \dot{E}_{\text{electrical}} = \dot{E}_{\text{electrical}} = A_m \times \eta_m \times I(t) \]

The rate of useful thermal exergy can be obtained as

\[ \dot{E}_{\text{exergy}} = m_f c_f (T_{fo} - T_f) - m_f c_f (T_D + 273) \ln \left( \frac{T_{fo} + 273}{T_{fo} + 273} \right) \]

The expression for hourly overall thermal energy yield based on the first law of thermodynamics can be defined as

\[ \dot{E}_{\text{thermal}} = \sum \dot{E}_{\text{thermal}} + \dot{E}_{\text{electrical}} \]

where \[ \dot{Q}_{\text{thermal}} = \dot{Q}_u \]

and the expression for overall exergy will be based on second law of thermodynamics is given by

\[ \dot{E}_{\text{exergy}} = \dot{E}_{\text{electrical}} + \dot{E}_{\text{exergy}} \]

**IV. METHODOLOGY**

The analysis of Cu/Al base PVT water collector have been done in order to obtain the annual energy and exergy gains. The methodology flow chart has been given in Fig. 4. The input data for the solar radiation and ambient air temperature has been taken from the India Meteorological Department (IMD), Pune, India.
V. RESULT AND DISCUSSION

In copper/aluminium (Cu/Al) base PVT water collector, due to the higher thermal conductivity of the copper (401 W/mK) and aluminium (207 W/mK), heat is transferred at a higher rate in comparison to glass and tedlar base PV module. Hence, more thermal energy can be obtained in Case III (Cu/Al base PV module) due to lower thermal resistance between different layers of the PV module. The bottom heat loss coefficient observed from solar cell to copper plate \( U_{b,cpcu} \) is 5.7 W/m²K and solar cell to aluminium plate \( U_{b,cpal} \) is also 5.7 W/m²K. Hence both the copper and aluminium plate gives similar performance in terms of energy and exergy.

The performance of the Cu/Al base PVT water collector has been studied for the climatic conditions of New Delhi, India. The data for the hourly variation of global solar radiation \( I_t \) and ambient air temperature \( T_a \) has been taken from the Indian Meteorological Department (IMD) Pune, India is shown in Fig. 4.

![Fig. 4. Hourly variation of solar radiation and ambient air temperature.](image)

The electrical efficiency of the PVT collector will depend upon the incident solar radiation and operating temperature of the solar cell. The electrical efficiency and average solar cell temperature for Case I (glass), Case II (Te) and Case III (Cu/Al) have been evaluated with the help of Eq. 13 as shown in Fig. 5. The electrical efficiency of Case I (glass) has been reported higher than that of Case II (Te) and Case III (Cu/Al) PV modules because of higher transmissivity and lower operating temperature achieved in glass.

![Fig. 5. Hourly variation of solar cell temperature and electrical efficiency](image)
flow rate of 0.017 kg/sec, the electrical efficiency of Case I is similar to Case IV as shown in Fig. 6.

![Fig. 6. Hourly variation of electrical efficiency at different mass flow rates](image)

The hourly variation of thermal energy of the aluminium/copper base PVT collector has been evaluated with water as a working fluid. The instantaneous thermal (characteristic curve) efficiency and exergy are shown in Fig. 7a & Fig. 7b.

![Fig. 7a Hourly variation of thermal energy of Cu/Al base PVT water collector](image)

![Fig. 7b Hourly variation of exergy of Cu/Al base PVT water collector](image)

The monthly yield in thermal energy and exergy yield at constant mass flow rate of 0.017 kg/s are shown in Fig. 8a & Fig. 8b. The monthly overall yield will depend upon the number of clear days. The number of clear days in different weather condition (A, B, C and D) for New Delhi weather station is given in Table 2. The maximum thermal energy and exergy is attained for the month of June for ‘C’ type weather condition as number of clear days is maximum in ‘C’ type weather condition.

![Fig. 8a Monthly variation of thermal energy yield for A, B, C, D type weather condition for New Delhi.](image)

![Fig. 8b. Monthly variation of exergy yield for A, B, C, and D type weather condition for New Delhi.](image)

![Table 2. Number of clear days for New Delhi climatic conditions](table)
VI. CONCLUSIONS

This study emphasizes on optimizing the performance of copper base PVT water heating system. The glass base, tedlar (Te) base and copper/aluminium (Cu/Al) base photovoltaics (PV) are analyzed without the flow of water in order to find the best configuration of the PV module. Several conclusions can be drawn from the results obtained from the analysis Case I, Case II, Case III and Case IV

i. The electrical efficiency of Case I (glass) PV is higher than that of Case II (Te) and Case III (Cu/Al) PV modules because of the higher operating temperature achieved in Case II and Case III.

ii. At mass flow rate of 0.017kg/sec the electrical efficiency of the Case IV (Cu/Al base PV water collector) is nearly equal to the electrical efficiency of Case I (glass).

iii. The hourly thermal and exergy efficiency of the Case IV (Cu/Al) PVT water collector are 61.65% and 13.35%.

iv. The net annual thermal energy and exergy gain obtained as 785.05 kWh and 106.67 kWh.

v. On the basis of present study, it is clear that copper/aluminium (Cu/Al) base PVT water collector is best designed system for the thermal and electrical needs.

Appendix

The relations used in the thermal modelling of the copper/aluminium (Cu/Al) base photovoltaic thermal (PVT) water collector system is given as follows:

\[(\alpha \tau_{m,eff}) = (\alpha_c - \eta_c) \tau_g \beta \text{ and } (\alpha \tau_{z,eff}) = \alpha_c (1 - \beta) \tau_g\]

Nomenclature

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Definition</th>
<th>Unit</th>
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<tbody>
<tr>
<td>A</td>
<td>area (m²)</td>
<td></td>
</tr>
<tr>
<td>W</td>
<td>breadth (m)</td>
<td></td>
</tr>
<tr>
<td>Dx</td>
<td>elemental length</td>
<td>h₀</td>
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<tr>
<td>αe</td>
<td>absorptivity of the photovoltaic cell</td>
<td>U_lca</td>
</tr>
<tr>
<td>εg</td>
<td>transmittivity of the glass</td>
<td>U_bcp</td>
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<tr>
<td>Tₑₑₑ</td>
<td>Solar cell temperature for Cu/Al base PV module</td>
<td>Tₑₑₑ</td>
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<tr>
<td>Tₑₑₑ</td>
<td>Solar cell temperature for glass base PV module</td>
<td>Tₑₑₑ</td>
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Inlet water temperature of the collector (°C)
Outlet water temperature at the end of collector (°C)
Heat transfer coefficient between PVT collector and ambient (W/m²K)
Overall heat transfer coefficient from cell to the ambient (W/m²K)
Overall heat transfer coefficient from photovoltaic cell to absorption plate (W/m²K) in Case I (glass base PV module)
Solar cell temperature for tedlar base PV module
Overall heat transfer coefficient from photovoltaic cell to absorption plate (W/m²K) in Case II (tedlar base PV module)
VII. REFERENCES


