Cost Analysis of a Combined Hybrid PV/T Model

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This study presents cost analysis for a design of hybrid photovoltaic thermal collector (PV/T) which works by dual coolants include of air and water. Annual cost of the collector (AC) and annual energy gain of collector (AEG) have been estimated. The ratio of AC/AEG evaluated at different values of variables which are mass flow rate of fluids, length of PV panel, channels depth and tubes dimension. The results for achieving proper design at mentioned variables are plotted at different figures. At the optimum point of figures, the ratio of AC/AEG is minimum value. By using the figures the optimized design features can easily be selected.

Key-Words: - Cost-benefit ratio analysis; cost-effectiveness; photovoltaic thermal collector.

1 Introduction

Photovoltaic thermal collector (PV/T) is a system in which PV acts as an absorber plate and generates electricity and absorbs heat by collector. In this system, power and heat are generated at the same time. In PV/T collectors, the most important consideration is to generate electricity, thus the PV systems should function at a low temperature with the purpose of keeping the electrical productivity in adequate level. To lower the temperature of the PV, fluids are used for cooling. Two main categories of PV/T are air type of PV/T collectors and water type of PV/T collectors.

Research regarding water type of PV/T was initiated around the mid of 1970s to early 1980s. The first study on the liquid base of PV/T collector was conducted by Wolf [1]. The first air PV/T collector that was integrated in a home described as “Solar One” was made by Professor Boer at the University of Delaware during 1973 and 1974. These collectors installed on the roof and facade of the Solar One house [2].

Some prior researchers have been done cost analysis study for two-pass solar air heater, triple-pass solar air heater and double-pass solar collector with and without fins [3-5]. This study will propose cost analysis for an integrated model of PV/T collector which is combined of both air type and water type of PV/T collectors in one unit. The optimized design of proposed model can be easily selected by presented results.

2 Proposed Model

The proposed system is a combined PV/T collector which consists of the water type of PV/T collector as well as air type of PV/T collector. The system’s conceptual patterns of combined hybrid photovoltaic thermal collector are shown in Figures 1 and 2 then named Combi-PV/T hereinafter. Below solar cells is covered by tedlar to give stability to the PV module. The whole PV/T collector as well as tubes surrounded by insulation.

The water type of PV/T as a part of design which is joined in Combi-PV/T is comprised of rectangular copper tubes. The attached tubes with no gap under PV module and insolated properly are assumed for having a high quality of heat transfer from PV module to water flowing.

The air type of PV/T as the other part of design which is joined in the Combi-PV/T is double-pass air PV/T collector. It is composed of upper channel and lower channel for flowing of air on both sides of PV module. Direction of air moving in the upper channel is in the direction of \( x \) and in the lower channel is moving in the reverse direction of \( x \).

A part of absorbed solar radiation by Combi-PV/T converts to electricity by PV panel and the rest produces heat energy. The main portion of this heat energy is removed from surface of PV module by air flowing as well as water flowing. Therefore, heat energy can be achieved by air and water at the outlet of Combi-PV/T collector.

3 Cost Analysis

The PV/T solar collector is cost-effective if it can obtain the most possible energy gain at least possible investment cost. The amounts ratio of AC/AEG for different variables (mass flow rate, length of PV panel, channels depth and tubes dimension) calculated and figures are plotted by MATLAB software.

3.1 Annual Energy Gain

The energy gain is comprised of thermal energy gain (TEG) and electrical energy gain (EEG) and defined per unit area of collector as follows:

\[ TEG = mCG_f(T_{out} - T_{in}) \]  
\[ EEG = \eta_{PV}\cdot I(t) \]  

The annual energy gain (AEG) considers total energy gain of collector in a year during operation time \( (t_{op}) \). It consists of annual thermal energy gain (ATEG) and annual electrical energy gain (AEEG) which are expressed as follows:

\[ ATEG = mCG_f(T_{out} - T_{in})t_{op} \]  
\[ AEEG = \eta_{PV}\cdot I(t)A_{c}P\cdot t_{op} \]  
\[ AEG = ATEG + AEEG \]  

3.2 Annual Cost

To calculate the annual cost (AC) has to evaluate some different cost of components per unit area of collector. These cost parameters are included of annual fanning and pumping cost (AFPC), annual collector cost (ACC), annual maintenance cost (AMC) and annual salvage cost (ASV) and expressed as follows:

\[ AC = AFPC + ACC + AMC - ASV \]  

The annual fanning and pumping costs (AFPC) is achieved with following relations. AFC1 is annual fanning cost due to upper channel, AFC2 is annual fanning cost due to lower channel and APC3 is annual pumping cost due to tubes as follows:

\[ AFC1 = \left( \frac{\dot{m}_1 \Delta P_1}{\rho} \right) t_{op} \cdot CE \]  
\[ AFC2 = \left( \frac{\dot{m}_2 \Delta P_2}{\rho} \right) t_{op} \cdot CE \]  
\[ APC3 = \left( \frac{\dot{m}_3 \Delta P_3}{\rho} \right) t_{op} \cdot CE \]  
\[ AFPC = AFC1 + AFC2 + APC3 \]

where \( \dot{m}_1, \dot{m}_2, \) and \( \dot{m}_3 \) are mass flow rates of fluids.

The pressure drops of air flow in upper channel and lower channel as well as pressure drop of water flow in tube are expressed with \( \Delta P_1, \Delta P_2 \) and \( \Delta P_3 \) respectively. The parameter CE is the cost of electricity. The pressure drop of air in upper channel and lower channel obtained by some presented relations in some studies [6, 7] as follows:

\[ \Delta P_1 = \left( \frac{\dot{m}}{A_{ap1}} \right)^2 \frac{1}{\rho} \left( \frac{L}{H_1} \right)^3 f_1 \]  
\[ \Delta P_2 = \left( \frac{\dot{m}}{A_{ap2}} \right)^2 \frac{1}{\rho} \left( \frac{L}{H_2} \right)^3 f_2 \]

Here \( A_{ap1} = H_1 \times L \) and \( A_{ap2} = H_2 \times L \) are air passage area for upper channel and lower channel respectively.

The parameters of \( f_1 \) and \( f_2 \) are friction factor for air flowing in channels which are expressed at different Reynolds numbers as follows:

\[ R_e < 2250 \rightarrow f = \left( \frac{24}{R_e} \right) + 0.9 \left( \frac{H}{L} \right) \]  
\[ 2250 < R_e < 10^4 \rightarrow f = 0.0094 + 2.92 (R_e)^{-0.15} \left( \frac{H}{L} \right) \]
The value of $H$ can be substituted by heights of upper channel ($H_1$) or lower channel ($H_2$) for calculating $f_1$ and $f_2$.

The pressure drop of water flowing inside tubes and related friction factor obtained by following relations [8, 9] as follows:

$$\Delta P_3 = f_3 \left( \frac{\bar{V}^2}{2} \right) \left( \frac{L}{D_h} \right) \rho$$

(3.2.11)

The friction factor for water flow in tubes calculated as follows:

$$R_e < 2100 \rightarrow$$

$$f_3 = \left( \frac{64}{R_e} \right)$$

(3.2.12)

$$R_e > 2100 \rightarrow$$

$$1 / \sqrt{f_3} = \left[ -2 \log \left( \frac{\epsilon}{D_h} \right)^{1.1098} + \frac{5.8506 \times 0.8981 R_e}{3.7065} \right]$$

(3.2.13)

where $\epsilon$ is roughness of copper 0.0013-0.0015 (mm) and $\frac{\epsilon}{D_h}$ is relative roughness which is dimensionless.

The annual cost of collector expressed as follows:

$$ACC = CRF \times CI$$

(3.2.14)

where CI is capital investment and CRF is capital recovery factor which are defined as follows:

$$CI = CAC + CSSC + FC$$

(3.2.15)

$$CRF = \frac{i((i+1)^n - 1)}{[(i+1)^n - 1]}$$

(3.2.16)

$$FC = 0.1 \times CI$$

(3.2.17)

The parameter of CAC is cost of collector array include of PV panel, insulation, back plate and copper tubes. Parameter CSSC is collector support structure cost and the fabrication cost (FC) is considered to be 10% of capital investment (CI). The annual maintenance cost (AMC) is considered to be 10% of annual collector cost (ACC).

The annual salvage value (ASV) is calculated by following relations where SFF is salvage fund factor and salvage value (SV) is considered to be 10% of capital investment as follows:

$$ASV = SFF \times SV$$

$$SFF = i/[(i+1)^n - 1]$$

(3.2.18)

(3.2.19)

4 Results and Discussions

The cost-effectiveness calculated by the use of related parameter and cost values as shown in table 1. The mass flow rates are varied from 0.01 to 0.1 kg/s. The channels depth are varied at the same manner ($H_1 = H_2$) from 0.01 to 0.1 m and PV panel length is varied from 1 m to 5 m. The width of rectangular tubes are varied from 0.01 to 0.05 m at constant value of tubes depth 0.01 m.

Firstly, the cost benefit ratio (AC/AEG) is calculated for Combi-PV/T, when air is flowing as coolant exclusively inside PV/T. The cost benefit ratio as function of channels depth are plotted in figures 3 and 4 for air mass flow rate of 0.03 and 0.06 kg/s respectively. It is indicated that the ratio of AC/AEG decreased at first as channels depth increased and then after reaching optimum point increased. Furthermore, the cost benefit ratio as function of PV panel length are plotted in figures 5 and 6 for air mass flow rates of 0.03 and 0.06 kg/s respectively. For almost straight lines, the ratio of AC/AEG increased with increase of PV panel length. Therefore the optimum point for such lines is between 1 to 2 m lengths of PV panel.

Table 1: The parameters and cost values for cost-effectiveness evaluation

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>Global solar radiation</td>
<td>$I_{(c)} = 700 W/m^2$</td>
</tr>
<tr>
<td>length of PV panel</td>
<td>$L = 1$ to $5$ m</td>
</tr>
<tr>
<td>mass flow rate</td>
<td>$m = 0.01$ to $0.1$ kg/s</td>
</tr>
<tr>
<td>Operational time</td>
<td>$300$ days and $8$ hours</td>
</tr>
<tr>
<td>Ambient temp</td>
<td>$T_a = 25^\circ C$</td>
</tr>
<tr>
<td>Inlet temp of water</td>
<td>$T_{in} = 25^\circ C$</td>
</tr>
<tr>
<td><strong>Cost parameters</strong></td>
<td></td>
</tr>
<tr>
<td>Collector array</td>
<td></td>
</tr>
<tr>
<td>Glass cover</td>
<td>$50$ RM/m²</td>
</tr>
<tr>
<td>Back plate</td>
<td>$90$ RM/m²</td>
</tr>
<tr>
<td>Insulation</td>
<td>$50$ RM/m²</td>
</tr>
<tr>
<td>Rectangular copper tubes</td>
<td>$300$ RM/m²</td>
</tr>
<tr>
<td>Photovoltaic panel</td>
<td>$1000$ RM/m²</td>
</tr>
<tr>
<td>Support structure</td>
<td>$50$ RM/m²</td>
</tr>
<tr>
<td>Solar collector life</td>
<td>10 years</td>
</tr>
<tr>
<td>Cost of electricity</td>
<td>$0.218$ RM/kWh</td>
</tr>
<tr>
<td>interest rate $(i)$</td>
<td>0.1</td>
</tr>
</tbody>
</table>
According to the figures 3-6, the optimum point achieved at channels depth between 0.065 and 0.07 m height and PV panel with 1 m length at air mass flow rates of 0.06 kg/s.

Secondly, the cost benefit ratio (AC/AEG) is calculated for Combi-PV/T with simultaneous fluids flowing (both air and water) at constant values of air mass flow rate 0.06 kg/s and channels depth 0.07 m.

The cost benefit ratio as function of tubes width are plotted in figures 7 and 8 for water mass flow rate of 0.01 and 0.06 kg/s respectively. It showed that the ratio of AC/AEG decreased at first as tube width increased and then after reaching optimum point increased. Furthermore, the cost benefit ratio as function of PV panel length are plotted in figures 9 and 10 for water mass flow rates of 0.01 and 0.06 kg/s respectively.
kg/s respectively. As shown in figures, the optimum point obtained for tube with 0.025 m width and 0.01 m depth as well as PV panel with 2 m length at air and water mass flow rates of 0.06 and 0.01 kg/s respectively.

Fig 9: AC/AEG as a function of PV panel length at different tubes widths (water mass flow rate = 0.01 kg/s)

Fig 9: AC/AEG as a function of PV panel length at different tubes widths (water mass flow rate = 0.06 kg/s)

5 Conclusion
The cost analysis of Combi-PV/T for obtaining the minimum ratio of AC/AEG is presented at different variables of design features. The optimum features of design is for tubes with 0.025 m width and 0.01 m depth include of PV panel with 2 m length in simultaneous mass flow rates of air and water at 0.06 kg/s and 0.01 kg/s respectively.

References: