Cost Analysis of a Single Pass, Double Duct Photovoltaic Thermal Solar Air Heater

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Abstract: - This paper presents economic analysis of the single pass, double duct photovoltaic thermal (PV/T) solar air collector with Compound Parabolic Concentrators (CPC) and fins. Evaluation of the annual cost (AC) and the annual energy gain (AEG) of the collector have been performed. The cost-benefit ratios of the collector (AC/AEG) were examined over a wide range of operational parameters (m, L, d₁ and d₂) to make it feasible for the users to select an optimum design and operational features which correspond to minimum (AC/AEG). The necessity for an economic analysis of the collector is obvious when assessing their feasibility in solar energy applications system. Results of the analysis are presented and discussed.

Key-Words: - Cost-benefit ratio; annual cost; annual energy gain; photovoltaic thermal collector.

1 Introduction
A photovoltaic-thermal (PV/T) solar air heater is a collector that combines solar thermal collector and photovoltaic cells in one single hybrid generating unit. It generates both thermal and electrical energies simultaneously. A new design of a single pass, double duct photovoltaic-thermal solar air heater with CPC and fins was successfully developed and fabricated at Universiti Kebangsaan Malaysia.

Extensive investigations have been carried out by many researchers on the design optimization of this hybrid collector. In the literature, a number of studies on economic optimization of conventional and hybrid solar air collectors have been made (Bhargava & Rizza 1986; Cox and Raghuraman 1985; Choudhury et al. 1995; Sopian & Othman 2000; Tripanagostopoulus et al. 2002; Tonui and Tripanagostopoulus 2007).

In this paper, a new design of a single pass, double duct photovoltaic thermal air collector with CPC and fins was studied. The collector design concept is shown in Figure 1. The objective of the optimization study is to able specifying design parameters, a combination of which can extract maximum possible thermal and electrical energy out of the available solar energy. The photovoltaic thermal collector becomes economically benefit, if it has the capability to collect the maximum amount of solar energy at minimum possible cost.

In this section, the performance and the cost factors of the collector is discussed, which lead to annual energy gain (AEG) and annual cost (AC) of the systems.

Fig. 1: The schematic diagram of a single pass, double duct (PV/T) solar air heater
2.1 Annual Cost (AC)

In order to determine the annual cost (AC) of the collector per unit surface area, the different cost factors have to be calculated. This include the annual pumping cost \((APC)\), the annual collector cost \((ACC)\), the annual maintenance cost \((AMC)\), and the annual salvage value \((ASV)\).

\[
AC = APC + ACC + AMC − ASV
\]

The annual pumping cost is calculated as,

\[
APC = \left(\frac{m \Delta P}{\rho}\right) t_{op} CE
\]

Where \(t_{op}\) is the operational time, \(CE\) is the cost of electricity, and \(\Delta \) is the pressure drop across each flow channel obtained by using the relations derived in Holland & Shewen (1981) and Kays & Perkins (1973) as follow,

\[
\Delta P = \left(\frac{m}{A_f}\right)^2 \left(\frac{1}{\rho}\right)^{\frac{3}{2}} \left(\frac{L}{H}\right)^{\frac{3}{2}} f
\]

Where \(A_f\) is the air passage area \((L \times H)\), \(f\) is the friction factor for different Reynolds number and calculated as,

\[
f = 0.0094 + 2.92 R_e^{-0.15} \frac{H}{L} \quad \text{for: } 2550 < R_e < 10^4
\]

\[
f = 0.059 R_e^{-0.2} + 0.73 \frac{H}{L} \quad \text{for: } 10^4 < R_e < 10^5
\]

The annual collector cost is calculated as,

\[
ACC = (CRF) (CI)
\]

Where \((CRF)\) is the capital recovery factor and calculated as,

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

Where \(i\) is the interest rate and \(n\) is the collector life time

The capital investment \((CI)\) is calculated as,

\[
CI = CAC + CSSC + FC
\]

Where \((CAC)\) is the cost of the collector array including the photovoltaic panel cost, \((CSSC)\) is the collector support structure cost, and \((FC)\) is the fabrication cost.

The annual maintenance cost \((MC)\) of the collector is considered to be 10 % of the annual collector cost \((ACC)\).

The annual salvage value \((ASV)\) is calculated as,

\[
ASV = (SFF)(SV)
\]

Where \((SFF)\) is the salvage fund factor and calculated as,

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

And

\[
SV = 0.1(CI)
\]

2.2 Annual Energy Gain (AEG)

The energy gain produced by the photovoltaic thermal solar collector are from two sources namely thermal and electrical energy. The thermal energy gain \((TEG)\) and the electrical energy gain \((EEG)\) per unit collector area from the collector can be determined by using the following equations:

\[
TEG = m C_p (T_o - T_i)
\]

\[
EEG = \eta_{pv}(I)
\]

The annual thermal energy gain \((ATEG)\) and the annual electrical energy gain \((AEEG)\) per unit collector area can be expressed as follows:

\[
ATEG = m C_p (T_o - T_i) t_{op}
\]

\[
AEEG = \eta_{pv} (I)(P)(A_c) t_{op}
\]

Where \(P\) is the packing factor \((0.44)\), \(A_c\) is the collector area, and \(t_{op}\) is the operational time.

Therefore; the annual energy gain of the single pass, double duct photovoltaic thermal solar collector can be expressed as follow:

\[
AEG = ATEG + AEEG
\]

The relevant data for cost-effectiveness calculations are shown in Table 1.
3 Numerical Results and Analysis

Numerical values of different parameters for single pass, double duct with CPC and fins are computed corresponding to an annual average radiation intensity of 700 W/m² and annual ambient temperature of 25°C for an operational time of 300 days during a year and 8 hours per day.

Table 1: Data for cost effective analysis

<table>
<thead>
<tr>
<th>Component</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>Annual average radiation</td>
<td>( I = 700 \text{ W/m}^2 )</td>
</tr>
<tr>
<td>Operational time</td>
<td>( t_{op} = 300 \text{ days / year, and 8 hours / day} )</td>
</tr>
<tr>
<td>Cost of glass cover</td>
<td>RM 40/m²</td>
</tr>
<tr>
<td>Cost of photovoltaic cells</td>
<td>RM 3023/m²</td>
</tr>
<tr>
<td>Cost of absorber plate</td>
<td>RM 87/m²</td>
</tr>
<tr>
<td>Cost of support structure</td>
<td>RM 20/m²</td>
</tr>
<tr>
<td>Cost of insulation</td>
<td>RM 26/m²</td>
</tr>
<tr>
<td>Cost of electricity</td>
<td>RM 0.218/kWh</td>
</tr>
<tr>
<td>Cost of fabrication</td>
<td>10% CI</td>
</tr>
<tr>
<td>Cost of maintenance</td>
<td>10% CI</td>
</tr>
<tr>
<td>Interest rate ((i))</td>
<td>10%</td>
</tr>
<tr>
<td>Collector life time ((n))</td>
<td>10 years</td>
</tr>
</tbody>
</table>

In this paper the depth of the upper and lower channels are assumed to be always same. The channel depth varies from 0.01 to 0.1 m. The collector length varies from 1 to 8 m. In addition, the mass flow rate is varied from 0.01 to 0.10 kg/s. Figures 2 and 3 show the cost benefit ratio for single pass, double duct PV/T collector with CPC and fins as a function of the channel depth for different collector length at mass flow rate equal to 0.04 kg/s and 0.08 kg/s. It can be seen that as the channel depth increases the AC/AEG first decreases and then increases. The optimum AC/AEG for this type of collector is obtained at the channel depth between 0.01 cm to 0.03 cm depends on the collector length and the mass flow rate.

Figure 3: AC/AEG as a function of the channel depth different collector length. \((m= 0.08 \text{ kg/s})\)

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Fig. 2: AC/AEG as a function of the channel depth at different collector length. \((m= 0.04 \text{ kg/s})\)

Figure 4 shows that at different collector length and different channel depth for single pass, double duct PV/T collector at mass flow rate equal to 0.04 kg/s. As seen in figure 4 at mass flow rate of 0.04 kg/s, the AC/AEG first decrease up to collector length of 4 to 5 m and then increase slightly. However, the increase seems to be the same for all collector length. Moreover, the optimum collector length where the AC/AEG is a minimum is observed between 1 and 3 m.

Figure 4: AC/AEG as a function of the collector length at different channel depth. \((m= 0.04 \text{ kg/s})\)

Figures 5 through 7 shows the effect of mass flow rate on AC/AEG and different channel depths at collector length equal to 1, 3, 5 m. At same collector length, as the mass flow rate increase the AC/AEG first decrease and then increase for different channel depths. It can be observed that it is more cost effective to operate the collector with smaller channel depths and lower mass flow rate.

Fig. 5: AC/AEG as a function of the collector length at different channel depth. \((m= 0.04 \text{ kg/s})\)
4 Conclusion

The cost-benefit ratios of the collector (AC/AEG) of the single pass, double duct PV/T air heater is presented for different combinations of collector design parameter. Hence, the designer can select the optimum design feature that corresponds to the minimum AC/AEG.

References: