Study of Thermal Performance of a Black Liquid Shallow Solar Pond Under Various Operating Conditions

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ABSTRACT

The shallow solar pond (S.S.P.) is a solar energy collection cum storage device suitable for domestic as well as industrial applications. A black liquid solar collector cum storage system is studied here. The liquid being black absorbs most of the radiation also the reflection losses from the water surface are very less. The performance prediction of the system has been done by the finite difference method for various operating conditions like intermittent flow, instantaneous flow, constant flow etc. A comparison of thermal performance of the black liquid system was done with a conventional and plastic bag S.S.P. and S.S.P. containing black liquid was found to be more efficient then other systems.

In a plastic bag S.S.P. the reflectance losses are reduced (6,8) and the system is more flexible and light in weight as compared to a conventional S.S.P. However, the conductive losses from the sides and bottom makes the system less efficient.

To avoid these drawbacks, a novel black liquid solar collector cum storage system is studied in this paper. It consists of a rectangular box made of P.V.C. material, containing the black liquid.

The use of P.V.C. material for such a system makes it convenient in moulding it any desired shape. The water in S.S.P. is replaced by black liquid thus the reflectance losses from the water surface are considerably reduced. A comparison between the thermal performance of the system was done with a conventional and plastic has S.S.P. and it was found that S.S.P. containing black liquid is more efficient under stagnant temperature conditions because this kind of composite system absorbs most of the radiation falling on black liquid where is an in a conventional S.S.P. there are heat losses in transfer of heat from the black absorber plate to the water and from the water to the fluid in the exchanger. It was observed that the mean outlet temperatures obtained in case of black liquid S.S.P is 4°C more than that in case of conventional S.S.P and about 8°C more in case of a plastic bag S.S.P.

2. Analysis

The analysis for the performance prediction of the system has been done by the forward step marching finite difference method and the outlet temperature and efficiency of the system has been predicted for various duty cycles according to the domestic requirements in a day. The various operating conditions considered are intermittent flow for one hour each at 11.00, 13.00 and 14.00 and 16.00 Hrs., constant temperature flow and no flow condition. The absorption of radiation in the case of conventional S.S.P. is taken by the superimposition of five exponential terms (5). And in case of the composite system, the study has been made by writing the heat balance equations for the black liquid, glass and the working fluid in the exchanger.
The hourly variation of solar radiation, ambient temperature and mass flow rate of exchanger fluid gives us the expression of a composite S.S.P. containing black liquid. Initially the glass cover and inlet water temperatures in the exchanger are assumed to be at the ambient temperature. The one dimensional heat balance equations at the glass surface and the black liquid are:

\[
\frac{dT}{dt} = \frac{M}{C_w} \left( S \cdot h_o (T - T_g) - h_w (T - T_w) \right) ... (2)
\]

\[
\frac{dT}{dt} = \frac{M}{C_w} \left( S \cdot h_o (T - T_g) - h_w (T - T_w) \right) + \frac{V_w}{C_w} \left( T - T_w \right) ... (3)
\]

Under no flow of exchanger fluid condition eqn. (3) becomes.

\[
\frac{dT}{dt} = \frac{M}{C_w} \left( S \cdot h_o (T - T_g) - h_w (T - T_w) \right) ... (4)
\]

In writing equation 2-4 it is assumed that the temperatures of the glass is uniform and there is no stratification in black liquid. Using the forward step marching finite difference technique \((3, 5)\) in which \(dT/dt\) is replace by \(V_w \cdot (T_{i+1} - T_i)\) and \(T_{i+1}\) are the values of the temperatures just before and just after the time interval \(t\). Equation (4) and (3) may be rewritten as:

\[
\frac{T_{i+1} - T_i}{V_w} = \frac{M}{C_w} \left( S \cdot h_o (T - T_g) - h_w (T - T_w) \right) + \frac{V_w}{C_w} \left( T - T_w \right) ... (5)
\]

Equation (5) and (6) can be solved simultaneously to give the temperature of the water. If the inlet temperature of exchanger is \(T\) then out let temperature of the exchanger is given by:

\[
T_{\text{out}} = T_{\text{in}} + \frac{V}{C_w} \exp \left( -\frac{S \cdot h_o (T - T_g) - h_w (T - T_w)}{M} \right) \frac{V_w}{C_w} \left( T - T_w \right) ... (7)
\]

This equation gives the outlet temperature of the waer in the exchanger.

In writing eqn. (7) it is assumed that the temperature of fluid around the exchanger is uniform. Also for a constant temperature flow, the varying mass flow rate is given by:

\[
\cdot \left( \frac{V}{C_w} \exp \left( -\frac{S \cdot h_o (T - T_g) - h_w (T - T_w)}{M} \right) \right)
\]

3. Results

Fig. 1 gives the ambient conditions for a typical summer day in New Delhi. In Fig. 2, the variation of water temperature for a shallow solar pond containing black liquid, a S.S.P. with a black absorbber and a plastic bag S.S.P. are shown for 12 hours of the day under similar ambient conditions. The maximum water temperatures attained for the three cases are found to be 60°C, 56.3°C and 55°C respectively.

In Fig. 3 and 4, the performance of a S.S.P. with black liquid is shown for different modes of hot water with-drawl and for different amounts of water stored. In Fig. 3a, the outlet temperature are shown for hot water with drawl for 1 hour each at 11.00, 14.00 and 16.00 Hrs. for two mass flow rates of 40Kg/hr and 60Kg/hr each. The system has 100Kg of stored water. We observe that even after the withdrawal of 120Kg and 180Kg of water respectively in the two cases mentioned above, the temperature of water stored in S.S.P. is 5° and 7°C above the ambient respectively.

In Fig. 3b, shows similar comparison for the 60Kg of stored water in the system. The temperature of stored water in the system after the intermittent withdrawal for three hours of 120Kg, 240Kg and 300Kg of hot water for 3 different cases is 3.5°C, 2°C and 1.5°C above the ambient.

Fig. 4a, b, show the outlet temperture for the case when hot water is withdrawn and for the case when hot water is withdrawn instantaneously at 10.00, 11.00, 12.00, 13.00, 14.00, 15.00, 16.00, 17.00 Hrs. each for 15 minutes for the mass flow rates of hot water stored in the system are taken to be 60 Kg and 100Kg.

Fig. 5 shows the mass flow rate of water with drawn with respect to time for a fixed constant temperature. The constant temperature taken are 40°C and 50°C.
<table>
<thead>
<tr>
<th>System Type</th>
<th>Mass of liquid in the pond (Kg)</th>
<th>Mass flow rate of exchanger fluid (Kg/hr)</th>
<th>Efficiency</th>
<th>Mode of heat withdrawal</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. S.S.P. Containing black liquid</td>
<td>100</td>
<td>0</td>
<td>40.08</td>
<td>No heat withdrawl</td>
</tr>
<tr>
<td>la.</td>
<td>100</td>
<td>60</td>
<td>55.3</td>
<td>Intermittent heat withdrawl for one hour at 11.00, 14.00, 16.00 Hrs.</td>
</tr>
<tr>
<td>lb.</td>
<td>60</td>
<td>100</td>
<td>58.8</td>
<td></td>
</tr>
<tr>
<td>lc.</td>
<td>20</td>
<td>100</td>
<td>47.7</td>
<td></td>
</tr>
<tr>
<td>Id.</td>
<td>100</td>
<td>20</td>
<td>54.3</td>
<td>Instantaneous heat withdrawl for 15 minutes at 10.00, 11.00, 13.00, 14.00, 15.00, 16.00, 17.00 Hrs.</td>
</tr>
<tr>
<td>le.</td>
<td>60</td>
<td>20</td>
<td>51.8</td>
<td></td>
</tr>
<tr>
<td>If.</td>
<td>20</td>
<td>100</td>
<td>61.1</td>
<td></td>
</tr>
<tr>
<td>lg.</td>
<td>100</td>
<td>Between 87.24 Kg/hr and 2.07 Kg/hr.</td>
<td>44.6</td>
<td>Constant temperature flow at 49°C.</td>
</tr>
<tr>
<td>2. Plastic Bag S.S.P.</td>
<td>100</td>
<td>0</td>
<td>32.3</td>
<td>No heat withdrawl</td>
</tr>
<tr>
<td>3. Conventional S.S.P.</td>
<td>100</td>
<td>0</td>
<td>34.8</td>
<td>No heat withdrawl</td>
</tr>
</tbody>
</table>

Reference

8. N.K. Bansal et. al. (1982) plastic solar air and water heaters made from different plastic materials.
Nomenclature

- $M_B$: Specific heat of glass cover per unit area ($J/Kg°C$)
- $C_{gB}$: Specific heat of glass cover ($J/Kg°C$)
- $S$: Solar Radiation ($W/m$) falling per unit area
- $h_f$: Heat transfer coefficient between glass cover and ambient ($W/ra°C$)
- $T_{cB}$: Temperature of glass cover ($°C$)
- $T_a$: Ambient temperature ($°C$)
- $h_2$: Heat transfer coefficient between glass cover and black liquid ($W/m°C$)
- $T_w$: Temperature of black liquid ($°C$)
- $M_w$: Heat capacity of black liquid per unit area ($J/m°C$)
- $C_w$: Specific heat of black liquid ($J/Kg °C$)
- $\Delta t$: Time difference (Sec.)
- $\omega$: Absorptance of black liquid
- $h_{bb}$: Heat transfer between glass cover and ambient ($W/m°C$)
- $h_{bb}$: Heat transfer between exchanger and black liquid ($W/m°C$)
- $T_{in}$: Inlet temperature of black liquid ($°C$)
- $C$: Constant
- $T_{out}$: Outlet temperature of exchanger fluid ($°C$)
- $T_{wo}$: Initial temperature of black liquid ($°C$)
- $T_{eo}$: Initial temperature of fluid in the exchange.