Effect of Plate Materials and Ambient Conditions on The Design of Flat Plate Solar Collector

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ABSTRACT

Flat plate solar collector radiation from the sun and transfer the received energy to a fluid which passing through pipes or channels which are integrating with the collector absorber plate that has a physical properties characterized by high absorptive solar radiation and low emission called the absorption surface, typically a metal plate, usually copper, aluminum alloy and steel materials with tubing of copper in thermal contact with the plates. In this paper simple and efficient thermal system has been designed to utilize the available sun light by simple design of flat plate solar collector under different conditions which includes different climatic conditions and different types of plate materials. For each case of above it was found outlet fluid temperature, instantaneous efficiency and modifier angle factor.

Keywords : Flat plate solar collector; Solar collector; thermal efficiency of collector

1. Introduction

In the recent years solar energy has been strongly promoted as an active energy source. One of the simplest and most direct applications of this energy is the conversion of solar radiation into heat. Hence way that the domestic sector can lessen its impact on the environment is by the installation of solar flat plate collectors for heating water. Although it should be said that some of these collectors have been in service for the last 40-50 years without any real significant changes in their design and operational principles. A typical flat-plate collector consists of an absorber in an insulated box together with transparent cover sheets (glazing) [1]. The absorber is usually made of a metal sheet of high thermal conductivity, such as copper or aluminum, with integrated or attached tubes Fig. 1. Its surface is coated with a special selective material to maximize radiant energy absorption while minimizing radiant energy emission. The insulated box reduces heat losses from the back and sides of the collector [2 - 3]. The flow distribution through the finned tubes of a collector clearly affects the operational efficiency of the collector system. Therefore, the more uniform the flow through the tubes, then the higher efficiency of the collector, and vice versa [4 - 5]. The flow distribution can be evaluated by temperature measurements at various points of the collector [6]. The energy loss through the top of solar collector is the result of convection and radiation between the parallel plates. The loss per unit area through the top is equal to the heat transfer from the absorber plate to the cover. This process of losing energy illustrated in fig.2.
to resist such heat. The absorber is usually made of metallic materials such as copper, steel or aluminum. The collector housing can be made of plastic, metal or wood, and the glass front cover must be sealed so that heat does not escape, and the collector itself is protected from dirt, insects or humidity. The absorber plate which covers the full aperture area of the collector must perform three functions: absorb the maximum possible amount of solar irradiance, transfer this heat into the working fluid at a minimum temperature difference and lose a minimum amount of heat back to the surroundings. Since the temperature of the absorber surface is above ambient temperature, the surface re-radiates some of the heat it has absorbed back to the surroundings. This loss mechanism is a function of the emittance of the surface for low-temperature, long-wavelength radiation. Many coatings that enhance the absorption of sunlight (short-wavelength radiation) also enhance the long wavelength radiation loss from the surface. A good coating will produce an absorber surface that is a good absorber of short-wavelength solar irradiance but a poor emitter of long-wavelength radiant energy. Normally the absorber is covered with one or more transparent cover sheets to reduce convective heat loss. However convective loss is not completely eliminated because a convective current exists between the absorber and the cover sheet, so transferring heat from the absorber to the cover sheet. External convection then produces a net heat loss from the absorber as it cools the cover sheet.

2. Theoretical background

Under steady conditions, the useful heat delivered by solar collector is equal to the energy absorbed in the metal surface minus the heat losses from the surface directly and indirectly to the surroundings. This principle can be stated in the relationship:

\[ Q_u = A_c \cdot HR \cdot (\tau \cdot \alpha) \cdot (T_p - t_f) \]

Where \( Q_u \) is the useful energy delivered by collector, [Watts] or [cal hr\(^{-1}\)]. \( A_c \) is the collector area, [m\(^2\)]. \( HR \) is the solar energy received on the upper surface of sloping collector, [W m\(^{-2}\)] or [cal hr\(^{-1}\) m\(^{-2}\)]. \( \tau \) and \( \alpha \) are the transmittance and absorptance, [dimensionless]. \( T_p \) is the power temperature of the absorber. \( t_f \) is the absorber temperature. The energy balance equation on the whole collector can be written as:

\[ Q_u = Q_a + Q_l + Q_t \]

Where \( Q_a \), is the rate of useful heat transfer to a working fluid in the solar heat exchanger, \( Q_l \) is the rate of energy losses from the collector to the surroundings, \( Q_t \) is the rate of energy storage in the collector. Collector efficiency \( \eta \) is the collector performance and is defined as the ratio of useful gain over any time period to the incident solar energy over the same time period.

\[ \eta = \frac{Q_u}{Q_a} \]

The constants \( C_1 \) and \( C_2 \) are found by substituting boundary conditions. The eq. 6 becomes:

\[ T_f - T_a - S/U_L = \frac{\cosh m}{\cosh m (W/D/2)} \]

The energy conducted to the region of the tube per unit length in the flow direction is

\[ q = q_{\text{f, base}} + q_{\text{t, section}} \]

Ultimately, the useful gain from the eq. 8 must be transferred into the fluid. The resistance to heat flow to the tube from the plant due to the wall thickness of the tube. Hence

\[ q_u = \frac{1}{C_p} \left[ \frac{1}{L_f} \int_{T_f}^{T_a} W F^1 \right] \]

For temperature distribution in the flow direction, consider the energy balance on the fluid element flowing through a pipe which is receiving a uniform heat flux \( q_u \) so that:

\[ m \cdot C_p \cdot \frac{dT_f}{dy} = \frac{m \cdot W F^1 \left[ S - U_L (T_f - T_a) \right]}{2} \]

If the assumption is made that \( F^1 \) and \( U_L \) are constant (and independent of \( y \)), then the solution of the differential equation for the temperature at any position (if subject to the condition that inlet fluid temperature is \( T_{in} \)) is:

\[ T_f - T_a - S/U_L = e^{-\frac{U_L}{C_p} \cdot \frac{m \cdot W F^1}{y}} \]

If the collector has length \( L \) in the flow direction, then the outlet fluid temperature \( T_f \) is found by substituting \( L \) for \( y \) in the eq. 17.
\[ T_{p} = T_{a} + \left( \frac{S}{U_{L}} \right) - \left( \frac{S}{U_{L}} - \left( T_{f} - T_{a} \right) \right) e^{-\frac{S}{U_{L}} t \cdot d \cdot \alpha \cdot \epsilon_{p} \cdot \rho_{p}} \]

Where: \( A_{c} = WL \), the area of the collector. The total useful energy collection rate \( Q_{u} \) may be expressed as:

\[ Q_{u} = m \cdot C_{p} \cdot \left( T_{f} - T_{a} \right) \]

Substituting for \( T_{r} \), already derived, gives:

\[ Q_{u} = A \cdot F_{g} \cdot \left( S - U_{L} \right) \left( T_{f} - T_{a} \right) \]

Where

\[ F_{g} = \frac{GC_{p}}{U_{L}} \left( 1 - e^{-\frac{S}{U_{L}} t \cdot d \cdot \alpha \cdot \epsilon_{p} \cdot \rho_{p}} \right) \]

\( F_{g} \) has been termed as the heat removal factor of the collector

3. Modeling and Design

The following tables represent steps of the main considerations that tack into account during modeling flat plate solar collector using EES soft program.

### Table 1. Test conditions

<table>
<thead>
<tr>
<th>State</th>
<th>( G_{t} ) [W/m²]</th>
<th>( G\alpha / G_{t} ) [%]</th>
<th>( \theta ) [deg]</th>
<th>( \beta ) [deg]</th>
<th>( T_{amb} ) [°C]</th>
<th>( V_{wind} ) [m/s]</th>
<th>( R ) [%]</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>1000</td>
<td>2</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>2.5</td>
<td>25</td>
</tr>
<tr>
<td>B</td>
<td>1000</td>
<td>2</td>
<td>30</td>
<td>30</td>
<td>30</td>
<td>40</td>
<td>25</td>
</tr>
<tr>
<td>C</td>
<td>1000</td>
<td>2</td>
<td>30</td>
<td>50</td>
<td>50</td>
<td>2.5</td>
<td>25</td>
</tr>
</tbody>
</table>

Efficiency curves based on temperature difference: \( T_{w} - T_{s} \)

### Table 2. Dimensions of collector

<table>
<thead>
<tr>
<th>Overall dimensions</th>
<th>Absorber dimensions</th>
</tr>
</thead>
<tbody>
<tr>
<td>L [m]</td>
<td>W [m]</td>
</tr>
<tr>
<td>W [m]</td>
<td>t [m]</td>
</tr>
<tr>
<td>L [m]</td>
<td>W [m]</td>
</tr>
<tr>
<td>2.91</td>
<td>1.221</td>
</tr>
<tr>
<td>0.079</td>
<td>2.4</td>
</tr>
<tr>
<td>1.137</td>
<td></td>
</tr>
</tbody>
</table>

\( L = \) Length, \( W = \) Width, \( t = \) Thickness (m), \( L_{p} = \) Length, \( W_{p} = \) Width

### Table 3. Properties of glass Cover

<table>
<thead>
<tr>
<th>Number of Cover</th>
<th>Properties of Cover 1</th>
<th>Properties of Cover 2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Solar Spectrum</td>
<td>Solar Spectrum</td>
<td></td>
</tr>
<tr>
<td>( n )</td>
<td>( t_{s} )</td>
<td></td>
</tr>
<tr>
<td>( \epsilon )</td>
<td>( \epsilon_{l} )</td>
<td></td>
</tr>
<tr>
<td>( \alpha )</td>
<td>( \alpha_{l} )</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>1.526 0.891 0.88 0</td>
<td></td>
</tr>
<tr>
<td></td>
<td>1.526 0.891 0.88 0</td>
<td></td>
</tr>
</tbody>
</table>

\( d_{c} \) = Cover plate air spacing = 1.8 [cm], \( d_{c1,c2} \) = Cover 1- cover 2 air spacing = 0.5 [cm]

### Table 4. Properties of Plate material

<table>
<thead>
<tr>
<th>Plate Material</th>
<th>( K_{p} ) [w/m.K]</th>
<th>( L_{p} ) [cm]</th>
<th>( d_{p} )</th>
<th>( \epsilon_{pl} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cu</td>
<td>380</td>
<td>0.02</td>
<td>0.88 0.15</td>
<td></td>
</tr>
<tr>
<td>Al – alloy 2024 T6</td>
<td>177</td>
<td>0.02</td>
<td>0.88 0.15</td>
<td></td>
</tr>
<tr>
<td>Plain carbon steel</td>
<td>60.5</td>
<td>0.02</td>
<td>0.88 0.15</td>
<td></td>
</tr>
</tbody>
</table>

\( K_{p} \) = user defined conductivity, \( t_{p} \) = Thickness, \( d_{p} \) = Absorbtance, \( \epsilon_{pl} \) = Emittance

### Table 5. Number and dimension of tube

<table>
<thead>
<tr>
<th>N</th>
<th>( d_{i} ) [cm]</th>
<th>( d_{o} ) [cm]</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>1.6</td>
<td>1.8</td>
</tr>
</tbody>
</table>

\( N \) = Number of Tubes, \( d_{i} \) = Inner diameter, \( d_{o} \) = Outer diameter

### Table 6. Properties of Fluid

<table>
<thead>
<tr>
<th>Material</th>
<th>( V' ) [L/min]</th>
<th>( P_{in} ) [KPa]</th>
<th>( K_{s} ) [w/m.K]</th>
</tr>
</thead>
<tbody>
<tr>
<td>Water</td>
<td>1</td>
<td>200</td>
<td>400</td>
</tr>
</tbody>
</table>

\( V' \) = Volumetric flow rate, \( P_{in} \) = Inlet pressure, \( K_{s} \) = Plate tube bond conductance

4. Results and discussion:

The instantaneous efficiency of flat plate solar collector have different type of plate materials and exposure into various temperature have great effects. Fig. 3, show the instantaneous efficiency of flat plate solar collector aluminum alloy and exposure into 30 °C start from 0.6 and decrease with increased of \( \Delta T/\Delta t \) when increase in to minimum value 0.35. Small match of the instantaneous efficiency between design and experimental has been shown. A little divergence of the instantaneous efficiency between design and experimental has been shown in solar collector has aluminum plate and exposure into same temperature as mentioned in fig. 6. In this case, the instantaneous efficiency start from 0.575, while the instantaneous efficiency of solar collector has carbon steel plate and exposure into same temperature is 0.512. In this context, large divergence of instantaneous efficiency between design and experimental as shown in fig. 9. In contrast, same behavior above of the instantaneous efficiency between design and experimental for solar collector have copper, aluminum alloy and carbon steel plate and exposure into 40 °C and 50 °C respectively. Just values of the instantaneous efficiency of solar collector changes from case of exposure into 30 °C, these values is obviously shown in figures 12, 15, 18, 21, 24 and 27 respectively.

Temperature distribution of flat plate solar collector has copper plate and exposure into 30 °C is shown in fig. 5, where 94.27 °C is the temperature of first cover glass, 59.27 °C is the temperature of second cover glass and 169.7 °C is the temperature of copper plate. Same temperature distribution is shown figures 8 and 11 for solar collector has aluminum alloy and plate respectively, and exposure into 30 °C. As the solar collector exposure into high temperature 40 °C, temperature distribution of the collector for first cover glass, second cover glass are 102.6 °C, 69.25 °C respectively and temperature of copper, aluminum alloy and carbon steel plate 177.8 °C as shown in figures 14, 17 and 20. When incident temperature increased in to 50 °C, temperature developed at solar collector are 111.6 °C, 79.9 °C, for first cover glass, second cover glass. Figures 23, 26 and 29 show 186.3 °C is the maximum temperature generated on the copper, aluminum alloy and carbon steel plate.

5. Conclusions

The instantaneous efficiency of flat plate solar collector greatly affected by incident temperature and type of plate materials. However, the values of the instantaneous efficiency extend from 0.6 to 0.25 with change of \( \Delta T/\Delta t \) for all various parameters of exposure temperature and type of plate materials. For all exposure temperature, closely match of the instantaneous efficiency between design and experimental clearly found in the case of copper plate, while a little and large divergence occurred in the cases of aluminum alloy and carbon steel plate respectively. In this context, at different exposure temperature, same temperatures are developed in plate for all type of materials.

![Figure 3. Instantaneous Efficiency of collector for copper plate at 30 °C](image)
Figure 4. Incident Ingle Modifier for copper plate at 30 °C

![Image](image1.png)

Figure 5. Temperature distribution for copper plate at 30 °C

![Image](image2.png)

Figure 6. Instantaneous Efficiency of collector for Aluminum alloy plate at 30 °C

![Image](image3.png)

Figure 7. Incident Ingle Modifier for Aluminum alloy plate at 30 °C

![Image](image4.png)

Figure 8. Temperature distribution for Aluminum alloy plate at 30 °C

![Image](image5.png)

Figure 9. Instantaneous Efficiency of collector for Plain carbon steel plate at 30 °C

![Image](image6.png)

Figure 10. Incident Ingle Modifier for Plain carbon steel plate at 30 °C

![Image](image7.png)

Figure 11. Temperature distribution for Plain carbon steel plate at 30 °C

![Image](image8.png)
Figure 12. Instantaneous Efficiency of collector for Copper plate at 40 °C

Figure 13. Incident Ingle Modifier for Copper plate at 40 °C

Figure 14. Temperature distribution for Copper plate at 40 °C

Figure 15. Instantaneous Efficiency of collector for Aluminum alloy plate at 40 °C

Figure 16. Incident Ingle Modifier for Aluminum alloy plate at 40 °C

Figure 17. Temperature distribution for Aluminum alloy plate at 40 °C

Figure 18. Instantaneous Efficiency of collector for Plain carbon steel plate at 40 °C

Figure 19. Incident Ingle Modifier for Plain carbon steel plate at 40 °C
Figure 20. Temperature distribution for Plain carbon steel plate at 40 °C

Figure 21. Instantaneous Efficiency of collector for Copper plate at 50 °C

Figure 22. Incident Ingle Modifier for Copper plate at 50 °C

Figure 23. Temperature distribution for Copper plate at 50 °C

Figure 24. Instantaneous Efficiency of collector for Aluminum alloy plate at 50 °C

Figure 25. Incident Ingle Modifier for Aluminum alloy plate at 50 °C

Figure 26. Temperature distribution for Aluminum alloy plate at 50 °C

Figure 27. Instantaneous Efficiency of collector for Plain carbon steel plate at 50 °C
Figure 28. Incident Ingle Modifier for Plain carbon steel plate at 50 °C

Figure 29. Temperature distribution for Plain carbon steel plate at 50 °C

REFERENCES


Nomenclature

$rc$ - Collector efficiency.  
$q_{tube}$ - Energy collected above the tube region, Watts.  
$q_u$ - Total energy gain of the collector, Watts.  
$C_b$ - Bond conductance  
$T_i$ - Inlet fluid temperature, °C.  
$T_o$ - Outlet fluid temperature, °C.  
$G _{S}$ - Incident Solar Radiation, W/m².  
$\theta$ - Incident Angle of Beam Radiation, deg.  
$\beta$ - Collector slope, deg.  
$T_{amb}$ - Ambient Temperature, °C.  
$V_{wind}$ - Wind speed, m/s.  
$F_1$ - Collector efficiency factor.  
$G_d/G_t$ - Diffuse Radiation proportion.  
$R$ - Relative Humidity.