Analysis of Solar Flat Plate Collector

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Abstract: Flat Plate Collector (FPC) is widely used for domestic hot-water, space heating/drying and for applications requiring fluid temperature less than 100°C. Three main components associated with FPC namely, absorber plate, top covers and heating pipes. The absorber plate is selective coated to have high absorptivity. It receives heat by solar radiation and by conduction; heat is transferred to the flowing liquid through the heating pipes. The fluid flow through the collector pipes is by natural (thermo syphon effect) or by forced circulation (pump flow). For small water heating systems natural circulation is used for fluid flow. Conventionally, absorbers of all flat plate collectors are straight copper/aluminum sheets however, which limits on the heat collection surface transfer area. Thus, higher heat collection surface area is optimized by changing its geometry with the same space of conventional FPC. The objective of present study is to evaluate the performance of FPC with different geometric absorber configuration. It is expected that with the same collector space higher thermal efficiency or higher water temperature can be obtained. Thus, cost of the FPC can be further bring down by enhancing the collector efficiency. A test setup is fabricated and experiments conduct to study these aspects under laboratory conditions (as per IS standard available for the flat plate collector testing).

The experimental results revealed that the performance of the solar water heater by using all the materials produced the maximum efficiency of around 40% to 47% respectively. And the maximum outlet water temperature reached is below 70°C respectively. The order of material priority for better efficiency is copper, aluminium, than stainless steel.

Keywords - Absorber plate emissivity, Flat plate collector, efficiency of collector, solar water heating.

I. INTRODUCTION

In the solar- In the solar-energy industry great emphasis has been placed on the development of "passive" solar energy systems, which involve the integration of several subsystems: Flat Plate collectors, heat-storage containers, fluid transport and distribution systems, and control systems. The major component unique to passive systems is the Flat plate collector. This device absorbs the incoming solar radiation, converting it into heat at the absorbing surface, and transfers this heat to a fluid (water) flowing through the Flat plate collector. The warmed fluid carries the heat either directly to the hot water or to a storage subsystem from which can be drawn for use at night and on cloudy days. Since 1900, a large number of solar collector designs have been shown to be functional; these have fallen into two general classes: Flat plate collectors: in which absorbing surface is approximately as large as the overall collector area that intercepts the sun's rays. Concentrating collectors in which large areas of mirrors or lenses focus the Sun light onto a smaller absorber. Since of energy crisis, there has been effort to develop new energy sources as a way to solve energy problem and at of there, solar energy has received special attention. The energy generated depends too much on time and seams to supply a stable power needed for a secondary energy source [1], [2].

1.1 Flat Plate Collector

Flat-plate collectors consist of (1) a dark flat-plate absorber, (2) a transparent cover that reduces heat losses, (3) a heat-transport fluid (air, antifreeze or water) to remove heat from the absorber, and (4) a heat insulating backing. The absorber consists of a thin absorber sheet (of thermally stable polymers, aluminum, steel or copper, to which a matte black or selective coating is applied) often backed by a grid or coil of fluid tubing placed in an insulated casing with a glass or polycarbonate cover. In water heat panels, fluid is usually circulated through tubing to transfer heat from the absorber to an insulated water tank. Flat Plate Collectors Of the many solar collector concepts presently being developed, the relatively simple flat plate solar collector has found the widest application so far. Its characteristics are known, and compared with other collector types, it is the easiest and least expensive to fabricate, install, and maintain. Moreover, it is capable of using both the diffuse and the direct beam solar radiation. For residential and commercial use, flat plate collectors can produce heat at sufficiently high temperatures to heat swimming pools, domestic hot water, and buildings; they also can operate a cooling unit, particularly if the incident sunlight is increased by the use of a reflector. Flat plate collectors easily attain temperatures of 40 to 70°C. With very careful engineering using special surfaces, reflectors to increase the incident radiation, and heat-resistant materials, higher operating temperatures are feasible. The main components of a flat plate solar collector [3], [4].

1.2 Types of Flat Plate Collector

1.2.1 Unglazed Solar Flat Plate Collectors

The term "unglazed water collector" refers to a solar water heating system that consists of a metal absorber without any glass or glazing over top. The most common type of
The main components of a flat plate solar thermal system are a dark colored flat plate absorber with an insulated cover, a heat transferring liquid containing antifreeze to transfer heat from the absorber to the water tank, and an insulated backing. The flat plate feature of the solar panel increases the surface area for heat absorption. The heat transfer liquid is circulated through copper or silicon tubes contained within the flat surface plate.

1.2.2 Flat Plate Solar Thermal Systems

Another common type of solar collector which has been in use since the 1950s. The main components of a flat plate panel are the highly desirable property of transmitting as much as 90% of the incoming shortwave radiation (solar), while virtually none of the long wave radiation emitted by the Flat plate can escape outward by transmission [8], [9].

1.3.2 Absorber Plates

The primary function of the absorber plate is to absorb as much as possible of the radiation reaching through the glazing, to lose as little heat as possible upward to the atmosphere and downward through the back of the container, and to transfer the retained heat to the circulating fluid. In general, absorption of solar energy impinging on an absorber plate should be as high as possible, but re-emission (loss) outward from the collector should be minimized [10].

1.3.3 Selective Coating

A surface that has a high absorptance and is a good absorber of solar radiation usually has a high infrared emittance as well and is a good radiator of heat. A flat-black paint that absorbs 96% of the incoming solar energy will also reradiate much of the energy as heat, the exact amount depending on the temperature of the absorber plate and the glazing. Ideally, one would like a surface to be selective, absorbing all the solar wavelengths and emitting none of the heat wavelengths, so that more heat could be transferred to the working fluid; for such a surface, α = 1 and ε = 0. Selective absorbers can be manufactured that approach this ideal, and several are available commercially [11], [12].
Flat-plate collectors must be insulated to reduce conduction and convection losses through the back and sides of the collector box. The insulation material should be dimensionally and chemically stable at high temperatures, and resistant to weathering and dampness from condensation. Usually, glass-wool insulation 10 cm thick is recommended. It would be better if the insulation also could contribute to the structural rigidity of the collector, but more rigid insulating materials are often less stable than glass wool [13], [14].

II. EXPERIMENTAL SETUP AND TEST PROCEDURE

Analysis is done on the flat plate collector of institution laboratory. It’s having a dimension of 1m wide and 2 m long and its collector plate is tilted at 60° for the normal incidence of solar irradiation. Tube having an inner diameter of 0.05cm thickness which is connected by 0.5cm thick plate at center to center distance of 10cm.

Two temperature sensors are used one for ambient temperature measurement and other is at outlet water condition. Water is to be circulating in the tube of solar plate collector and hot water comes out from outlet and temperature of which is measured by temperature sensor. The Natural circulation solar water heater was tested in the month of May, 2016 at intervals of between 9.00 am to 3 pm. The incident solar radiation intensity was measured by using pyranometer. The water inlet and outlet temperature for the collector as well as ambient air is with a precision of 0.5°C. Experimental analysis is done on the three collector plate material namely as copper, aluminium and stainless steel.

Observation Table

Inlet water temperature = 26°C (for all materials)

Table 2.1 Observation table for copper

<table>
<thead>
<tr>
<th>S. No</th>
<th>Time</th>
<th>Outlet water temperature(°C)</th>
<th>Ambient temperature (°C)</th>
<th>Irradiation (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>9am</td>
<td>52</td>
<td>30</td>
<td>152.58</td>
</tr>
<tr>
<td>2.</td>
<td>11am</td>
<td>63</td>
<td>34</td>
<td>363.84</td>
</tr>
<tr>
<td>3.</td>
<td>1pm</td>
<td>70</td>
<td>38</td>
<td>575.81</td>
</tr>
<tr>
<td>4.</td>
<td>3pm</td>
<td>61</td>
<td>36</td>
<td>380.88</td>
</tr>
</tbody>
</table>

Table 2.2 Observation table for aluminium

<table>
<thead>
<tr>
<th>S. No</th>
<th>Time</th>
<th>Outlet water temperature(°C)</th>
<th>Ambient temperature (°C)</th>
<th>Irradiation (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>9am</td>
<td>45</td>
<td>31</td>
<td>297.15</td>
</tr>
<tr>
<td>2.</td>
<td>11am</td>
<td>56</td>
<td>33</td>
<td>403.18</td>
</tr>
<tr>
<td>3.</td>
<td>1pm</td>
<td>66</td>
<td>38</td>
<td>809.56</td>
</tr>
<tr>
<td>4.</td>
<td>3pm</td>
<td>58</td>
<td>35</td>
<td>455.37</td>
</tr>
</tbody>
</table>
2.2 Equations and Measurement

If I am the intensity of solar radiation, in W/m², incident on the aperture plane of the solar collector having a collector surface area of A, m², then the amount of solar radiation received by the collector is:

\[ Q_i = I.A \]  

(a)

However, as it is shown Figure 2, a part of this radiation is reflected back to the sky, another component is absorbed by the glazing and the rest is transmitted through the glazing and reaches the absorber plate as short wave radiation. Therefore the conversion factor indicates the percentage of the solar rays penetrating the transparent cover of the collector (transmission) and the percentage being absorbed. Basically, it is the product of the rate of transmission of the cover and the absorption rate of the absorber.

Thus

\[ Q_i = I(\tau \alpha).A \]  

(b)

As the collector absorbs heat its temperature is getting higher than that of the surrounding and heat is lost to the atmosphere by convection and radiation. The rate of heat loss \( Q_o \) depends on the collector overall heat transfer coefficient \( UL \) and the collector temperature.

\[ Q_o = UL.A(T_c - T_a) \]  

(c)

Thus, the rate of useful energy extracted by the collector \( Q_u \), expressed as a rate of extraction under steady state conditions, and is proportional to the rate of useful energy absorbed by the collector, less the amount lost by the collector to its surroundings.

This is expressed as follows:

\[ Q_u = Q_i - Q_o = I \tau \alpha A - UL.A(T_c - T_a) \]  

(d)

It is also known that the rate of extraction of heat from the collector may be measured by means of the amount of heat carried away in the fluid passed through it, that is:

\[ Q_u = mC_p(T_o - T_i) \]  

(e)

Equation (e) proves to be somewhat inconvenient because of the difficulty in defining the collector average temperature. It is convenient to define a quantity that relates the actual useful [15], [16] energy gain of a collector to the useful gain if the whole collector surface were at the fluid inlet temperature. This quantity is known as “the collector heat removal factor \( Fr \)” and is expressed as:

\[ Fr = \frac{mC_p(T_o - T_i)}{I \tau \alpha A - UL.A(T_c - T_a)} \]

\[ Fr = \frac{mC_p}{AcUL} \left[ 1 - \exp \left( -\frac{AcUL}{mC_p} \right) \right] \]  

(f)

The maximum possible useful energy gain in a solar collector occurs when the whole collector is at the inlet fluid temperature. The actual useful energy gain \( Q_u \), is found by multiplying the Collector heat removal factor \( Fr \) by the maximum possible useful energy gain. This allows the rewriting of equation (f)

\[ Q_u = Fr.A[I \tau \alpha - UL(T_i - T_a)] \]

Equation is a widely used relationship for measuring collector energy gain and is generally known as the “Hottel-Whillier-Bliss equation”.

A measure of a flat plate collector performance is the collector efficiency \( \eta \) defined as the ratio of the useful energy gain \( Q_u \) to the incident solar energy over a particular time period

\[ \eta = \frac{\int Q_u \, dt}{A \int I \, dt} \]

The instantaneous thermal efficiency of the collector is:

\[ \eta = \frac{Q_u}{A \int I \, dt} \]

\[ \eta = Fr. \tau \alpha - FrUL \frac{(T_i - T_a)}{I} \]

Fr value 0.845, 0.9707, 0.999 for copper, aluminium and stainless steel plate respectively which is calculated by formula (f)

UL value for copper aluminium and stainless steel are 13.1, 25.47, 3 W/m²-k

It is assumed that FR, \( \tau \), \( \alpha \),UL are constants for a given collector and flow rate, then the efficiency is a linear function of the three parameters defining the operating condition: Solar irradiance \( I \), Fluid inlet temperature \( T_i \) and Ambient air temperature \( T_a \). Thus, the performance of a Flat-Plate Collector can be approximated by measuring these three parameters in experiments.

III. RESULT AND DISCUSSION

3.1 Efficiency result for copper

Efficiency of solar plate collector is calculated by above formula and observation is taken by table

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Time</th>
<th>Outlet water temperature (°C)</th>
<th>Ambient temperature (°C)</th>
<th>Irradiation (W/m²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>9am</td>
<td>41</td>
<td>29</td>
<td>143.18</td>
</tr>
<tr>
<td>2.</td>
<td>11am</td>
<td>53</td>
<td>33</td>
<td>376.37</td>
</tr>
<tr>
<td>3.</td>
<td>1pm</td>
<td>62</td>
<td>39</td>
<td>829.60</td>
</tr>
<tr>
<td>4.</td>
<td>3pm</td>
<td>51</td>
<td>35</td>
<td>509.90</td>
</tr>
</tbody>
</table>
Table 3.1 Efficiency of copper plate

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Time</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>9am</td>
<td>39.42</td>
</tr>
<tr>
<td>2.</td>
<td>11am</td>
<td>44.1</td>
</tr>
<tr>
<td>3.</td>
<td>1pm</td>
<td>45.31</td>
</tr>
<tr>
<td>4.</td>
<td>3pm</td>
<td>42.0</td>
</tr>
</tbody>
</table>

3.2 Efficiency result for alluminium

Efficiency of solar plate collector is calculated by above formula and observation is taken by table

Table 3.2 Efficiency of alluminium plate

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Time</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>9am</td>
<td>31.79</td>
</tr>
<tr>
<td>2.</td>
<td>11am</td>
<td>36.5</td>
</tr>
<tr>
<td>3.</td>
<td>1pm</td>
<td>42.66</td>
</tr>
<tr>
<td>4.</td>
<td>3pm</td>
<td>36.0</td>
</tr>
</tbody>
</table>

3.3 Efficiency result for stainless steel

Efficiency of solar plate collector is calculated by above formula and observation is taken by table

Table 3.3 Efficiency of stainless steel plate

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Time</th>
<th>Efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>9am</td>
<td>27.79</td>
</tr>
<tr>
<td>2.</td>
<td>11am</td>
<td>33.5</td>
</tr>
<tr>
<td>3.</td>
<td>1pm</td>
<td>40.65</td>
</tr>
<tr>
<td>4.</td>
<td>3pm</td>
<td>35.8</td>
</tr>
</tbody>
</table>

1. The first is the maximum collection efficiency, called the optical efficiency. This occurs when the fluid inlet temperature equals ambient temperature (T_i = T_a). For this condition, the ΔT/I value is zero and the intercept is FR(τ α).

2. The other point of interest is the intercept with the ΔT/I axis. This point of operation can be reached when useful energy is no longer removed from the collector, a condition that can happen if fluid flow through the collector stops (power failure). In this case, the optical energy coming in must equal the heat loss, requiring that the temperature of the absorber increase until this balance occurs. This maximum temperature difference or “stagnation temperature” is defined by this point. For well-insulated collectors or concentrating collectors the stagnation temperature can reach very high levels causing fluid boiling and, in the case of concentrating collectors, the absorber surface can melt.

3. The relationship between efficiency with the time is shown in the below graph for different materials.

Graph: Efficiency v/s time graph

The collector efficiency is also compared with three different cases and its depicted fig. The collector efficiency at 9am is 39.42% for copper riser tubes, 31.79% expected for aluminum tubes riser tubes and 27.79% for stainless steel riser tubes. The maximum efficiency is observed at the time 1pm in three cases as 45.31%, 42.66% (expected) and 40.65% respectively. The collector efficiency is decreasing after 1pm till 3pm in the same manner. The efficiency of solar plate collector is shown in graph 10.2. The graph reveals that the maximum efficiency is at 1pm in the three different cases.

4. Temperature range and efficiency of the different materials observed at different temperature are shown in the below table.

Table 3.4 Temperature and efficiency range of materials

<table>
<thead>
<tr>
<th>S No.</th>
<th>Materials</th>
<th>Temperature range (9am – 3pm)</th>
<th>Efficiency range (9am – 3pm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.</td>
<td>Copper plate</td>
<td>52°C - 70°C</td>
<td>39.42% - 45.31%</td>
</tr>
<tr>
<td>2.</td>
<td>Aluminium plate</td>
<td>45°C - 66°C</td>
<td>31.79% - 42.66%</td>
</tr>
<tr>
<td>3.</td>
<td>Stainless steel</td>
<td>41°C – 62.5°C</td>
<td>27.79% - 40.65%</td>
</tr>
</tbody>
</table>

The results shows the maximum temperature of the peak solar irradiation during the test at a maximum water temperature of 70°C for copper plate, 66°C for aluminium plate and 62.5°C in stainless steel plate are obtained. The solar intensity is increasing from 9am to 1pm, reaching a maximum value of 829 W/m² at 1pm. The outlet temperature measured at 9am is 52°C, 45°C and 41°C for copper riser tubes aluminium tubes coated with copper oxide and stainless steel tubes coated with epoxy-polyether riser tubes respectively. The maximum outlet temperatures were recorded at 2pm for all three cases. The outlet temperature reduced after 2pm until 5pm for all three cases.

IV. CONCLUSION

- The result records that the collector outlet temperature has the function of solar irradiance and time.
• The maximum collector efficiency was obtained at 1pm in the experiments.
• The experimental results revealed that the performance of the solar water heater by using all the materials produced the maximum efficiency of around 40% to 47% respectively.
• The maximum outlet water temperature reached is below 70°C respectively.
• The order of material priority for better efficiency is copper, aluminium, than stainless steel.

V. SCOPE FOR FUTURE WORK
The present study can be extended in the following direction:
1. Experiment can be performed by other different material.
2. Size variation can be done for better efficiency.
3. Optimization can be performed at varied tilt angle of solar flat collector.
4. Cost analysis can also be performed by using other materials.

REFERENCES
[3]. S.A. Kalogirou, Y. Tripanagnostopoulos (30 January, 2006). These systems are most often used for domestic hot water (DHW) and electricity production.