Analysis of Solar Steam Generation Device and Effect of Black Coating for Receiver

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Abstract - This paper presents the present scenario of solar water heating system and Solar Concentrated Power. From study it is observed that there is no any device which can be used for the generation of high temperature water or low temperature steam. At present flat plate collectors are used to heat the water. Flat plate collectors cannot achieve high temperature which is sufficient for steam generation. As present system unable to provide the steam the steam generation device will play a role to increase percent of solar energy in industrial process heat. If CSP is used for water heating the boiling temperature and the steam generation can be achieved with the help of solar energy. This steam can be directly used for various low pressure applications. Also in the Solar Steam generating device if Black Coating is done for receiver it improves the efficiency of system and output energy of the steam. Black epoxy coating improves the absorptance of the receiver surface and thus increase the amount of energy absorbed which reflects on it by collecting surface. Simultaneously temperature of the system improves which causes to increase the convective losses from the system. But due to improved energy absorptance this increment doesn’t affect the efficiency worst. This type of coating can improve the efficiency of the system. Thus one can achieve improved quality of output steam. Paper presents the actual development of device, testing and analysis of the test results. Paper also explains the experimental results which show the effect of black coating for receiver on the efficiency and energy collected by the system.

Key Words: Concentrated Solar Power (CSP), Solar Water Heating, Steam generation, Black epoxy coating to improve efficiency of system.

1. INTRODUCTION

Concentrated solar is type of solar system which allows the effective collecting and concentrating of the incoming solar irradiation. The concentrator receives approximately 1.064 kW/m2 of solar insolation (dependent upon time of year), which is concentrated and reflected to the receiver with less area. By concentrating the incoming radiation, the operating temperature of the system is increased significantly, and subsequently increases the efficiency of the conversion from sunlight to thermal energy.

At present, there are four main CSP technology families, which can be categorized by the way they focus the sun’s rays and the technology used to receive the sun’s energy:

1. Parabolic Troughs (Line Focus, Mobile Receiver)
2. Linear Fresnel Reflectors (Line Focus, Fixed Receiver)
3. Solar Towers (Point Focus, Fixed Receiver)
4. Parabolic Dishes (Point Focus, Mobile Receiver)

The basic principle of solar thermal collection is that when solar radiation is incident on a surface (such as that of a black-body), part of this radiation is absorbed, thus increasing the temperature of the surface. As the temperature of the body increases, the surface loses heat at an increasing rate to the surroundings. Steady-state is reached when the rate of the solar heat gain is balanced by the rate of heat loss to the ambient surroundings.

Two types of systems are used to utilize this solar thermal conversion. 1) Passive systems

Passive system is considered, in which an external solar collector with a heat transfer fluid is used to convey the collected heat.

2) Active systems

Active system doesn’t need any additional working fluid or the system required to circulate it.

As present system unable to provide the steam the steam generation device will play a role to increase percent of solar energy in industrial process heat. Concentrated solar system is not used in the domestic sector. With application of proposed system solar concentrator can applicable with the domestic use. It is also found that, parabolic dish collectors installed in various locations in India are used for solar steam cooking applications. When this two system are combined they can be useful for various industrial sector where low pressure steam is used for various processes. These applications are briefly shortlisted below.
Table 1 Industrial Applications of Low pressure Steam

<table>
<thead>
<tr>
<th>Industry</th>
<th>Pressure (bar)</th>
<th>Flow Rate (kg/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bakeries</td>
<td>1</td>
<td>10</td>
</tr>
<tr>
<td>Restaurants</td>
<td>1</td>
<td>100</td>
</tr>
<tr>
<td>Hospitals</td>
<td>3</td>
<td>150</td>
</tr>
<tr>
<td>Paper Production</td>
<td>1</td>
<td>7</td>
</tr>
<tr>
<td>Creameries and Dairies</td>
<td>0.3 – 3</td>
<td>200</td>
</tr>
</tbody>
</table>

It can overcome the drawback of traditional solar water heater. It can supply steam at required pressure for end use. However, the efficacy of conversion for economical industrial application is needed.

2. Design and Development of the system
   Methodology for system design
   1. Material selection consideration for various system components
   2. Material selection based on the availability and working conditions
   3. Detailed theoretical design for of the each components
   4. Specification finalization for the system with modification from practical constraints
   5. Proposed system details
   6. System after manufacturing

Material Selection
Materials for all components are selected as per the standard guidelines for the material selection for solar concentrating and stem generation devices. Important selection is for black coating to improve the efficiency of the system.

Black epoxy paint used for the receiver coating. Black coating improves the radiation absorbance of the receiver plate. Thus experiments are carried out for receiver with black coating and receiver without black epoxy coating.

   a. Absorbance-Transmittance factor for black pint
   b. Optical and thermal properties of the paint

Design details and proposed system:
Load on the system to be designed is finalized based on the system output requirement and depending steam quality required.

Final Specification of the System parameters
Amount of water to be converted into steam = 1.5 kg/hr Minimum pressure at which steam is extracted from the absorber = 1.5 bar Maximum pressure at which steam is allowed to heat = 3.0 bar
1. Finalize the Specification for the Concentrator dish
   Surface area of the Concentrator dish = 1.54 m²
   Focal length of the concentrator dish = 0.3223 m
2. Finalize the specifications for the absorber cylinder
   Minimum internal diameter of the absorber cylinder = 190 mm
   Minimum Height of the absorber cylinder = 130 mm
   Minimum thickness of the absorber cylinder = 2.235 mm

3. Use of Black Epoxy coating
Selection of the coating for the receiver surface is based on the following conditions. The selected coating surface should consider the following properties.
   a) Receiver should be good absorber of heat energy
   b) Receiver should have high thermal conductivity
   c) Receiver should have low thermal resistance
   d) Receiver should not be corrosive
   e) Receiver should withstand high temperature

Black epoxy paint used for the receiver coating. Black coating improves the radiation absorbance of the receiver plate. Thus experiments are carried out for receiver with black coating and receiver without black epoxy coating.

   a. Absorbance-Transmittance factor for black pint
   b. Optical and thermal properties of the paint

Value of Absorbance-Transmittance factor for the receiver surface without black coating is

\[ \rho_{AL} \times \alpha_{AL} = 0.7. \]
Simultaneously this value for Black Coating is 
\[ \rho_{BC} \times \alpha_{BC} = 0.94. \]

From this values the difference between collected energy can be find out which will be higher for the receiver with black coating. So the receiver temperature and usefulness energy gain will increase for black coating.

4. Testing and Performance Evaluation

**Figure 3:** Experimental Setup for Testing of system without black coating

**Testing Methodology**

The system specifications are finalized for 1.5 liter of water heating with aluminum absorber, vertical cylinder type. A cooker made of aluminum with the given dimensions is fitted at the focal point of reflector which will fall below the top horizontal surface, so as to enable to fix the top glass cover during the experimentation. The schematic is shown in figure 2.

1. Concentrating solar collector -with Aluminium-without coating absorber CSC-A with 1.5 liter water capacity
2. Concentrating solar collector -with Aluminium-with absorber Coating CSC-A with 1.5 liter water capacity

**Figure 4:** Receiver surface with black coating

**Performance Evaluation of the Proposed System**

Theoretical performance analysis of the system can done one basis of the theory developed as follows. One has to calculate total available energy and total losses in the system to calculate the performance of the system. Methodology for the performance evaluation can explained as follows

1. Calculate the Total solar radiations available at the plane of the system.
2. Find out the total energy collected by the concentrator
3. Calculate total amount of heat loss at receiver
4. Calculate total amount of heat loss in steam piping
5. Evaluate the performance of the system in the form of collector efficiency and system efficiency.
6. Proposed parameters that have to be recorded for performance evaluation in experimental method.

**Formulas for performance evaluation**

1. \[ Q_{OPTAINED} = \Gamma \times (\rho_{AL} \times \alpha_{AL}) \times E_{INC} \]
   \[ \Gamma = \text{capture fraction for receiver} \]
   \[ \rho_{AL} \times \alpha_{AL} = 0.7 = \text{reflectance absorptance product for receiver material}. \]
2. \[ Q_{loss} = A_r \times U_l \times (T_r - T_a) \]
   \[ A_r = \text{Area of receiver} \]
   \[ U_l = \text{Overall Heat loss coefficient} \]
   \[ T_r = \text{Receiver temperature} \]
   \[ T_a = \text{Temperature of air surrounding a receiver} \]
3. \[ U_l = h_{conv} + h_{rad} \]
   \[ h_{conv} = \text{Convective heat loss coefficient} \]
   \[ h_{rad} = \text{Radiative heat loss coefficient} \]
4. Collector efficiency \[ \eta_{collector} = \frac{Q_{OPTAINED} - Q_{RECEIVER LOSS}}{Q_{INC}} \]
5. Collector efficiency \[ \eta_{collector} = \frac{Q_{OPTAINED} - Q_{RECEIVER LOSS} - Q_{PIPE LOSS}}{Q_{INC}} \]

Data is collected for both of the test setups and above specified calculations are carried out. From this calculations and detailed data analysis following reading is found.

**Table 2 results for Experiments on system efficiency**

<table>
<thead>
<tr>
<th>Case</th>
<th>Average Solar Radiation</th>
<th>Temperature</th>
<th>Steam Pressure</th>
<th>Time to achieve 1.5 bar (min)</th>
<th>System efficiency (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Receiver (°C)</td>
<td>Steam inside receiver (°C)</td>
<td>Receiver (bar)</td>
<td>Achieved</td>
<td>Averag</td>
</tr>
<tr>
<td>Case 1A</td>
<td>1100</td>
<td>155</td>
<td>140</td>
<td>1.92</td>
<td>1.7</td>
</tr>
<tr>
<td>Case 1B</td>
<td>975</td>
<td>125</td>
<td>120</td>
<td>1.68</td>
<td>1.5</td>
</tr>
<tr>
<td>Case 2A</td>
<td>950</td>
<td>160</td>
<td>135</td>
<td>3.1</td>
<td>3.0</td>
</tr>
<tr>
<td>Case 2B</td>
<td>900</td>
<td>150</td>
<td>110</td>
<td>2.0</td>
<td>1.8</td>
</tr>
</tbody>
</table>
5. Effect of Black Epoxy coating
Black coating on receiver increases the energy absorbed by the receiver. Receiver without coating has the reflectance absorptance product of 0.7. Same value for the receiver with black coating is equal to 0.94. This increase in absorptance- reflectance factor causes nearly 30% increase in absorbed energy for the same amount of solar radiation.

This effect can studied on the three basic criteria
1. Effect on temperature
2. Effect on Useful Heat Gain
3. Effect on System efficiency

Effect on Receiver Temperature

From the above graphs it can be seen that as one use the black coating for the receiver the surface temperature for the receiver increases.

1. Maximum and average surface temperature will be increased by 15°C - 20°C.

Effect on Useful Heat Gain

From the graph it is seen that as the radiation increases total heat gain also increases. The effect of glass cover total useful heat gain increases for same amount of solar radiation. If we consider the values of total useful heat gain for 1000 watt of solar radiation results are:

1. Without glass cover total heat gain for 1000 watt solar radiation is nearly 550 watt.
2. With glass cover same value will be nearly about 700 watt.
3. Thus one can conclude that total heat gain will increase by 25%-30% at the 1000 watt solar radiation.
Effect of receiver coating on the system efficiency for receiver
without glass cover is shown in the graphs.

1. Average efficiency for receiver without black coating is nearly 51-54%
2. Average efficiency for receiver with black coating is nearly 71-74%
3. Average increase in efficiency is 20%, efficiency becomes 1.4 of actual value due to black coating.

6. Results and Conclusion

It is observed that a system producing steam for solar heating of water will be very useful in the industrial and commercial sectors. This system can help to reduce the load on the electrical and Fossil fuel energy used to steam generation. Also with the help of black coating it is easy to achieve boiling temperature as well as to improve the efficiency of the system. Receiver surface temperature increases by 27 % as compared non coated receiver, it increases thermal conductivity of air surrounding the receiver, and hence therefore a increases convective & radiative heat losses from receiver by 36 %. Thus overall heat loss from receiver increases by 36 %. With black coated receiver useful heat gain is increased by 10 % As compared to non coated receiver collector efficiency is increased by 17.5%For 36 % rise in total heat losses, collector efficiency is increases by 17.5 % & overall heat loss coefficient increases by 7.35 % as compared non coated receiver. Time taken to produce steam is also reduced with use of black coating. Black coating applied reduce time to produce steam is reduced from 30 min to 17min.

7. Recommendations

System described above can be optimized for following reasons System can be converted into continuous steam generation system with use of water pumping system and valves. It can be used to supply steam for instantaneous steam generation requirement. Performance improvement is possible with the experimental evaluation. Automatic tracking system either mechanical or hydraulic can be used. By variation of coating materials, performance of system can be evaluated. Heat losses in the steam pipe and steam generator can reduced with proper coating material. Commercial models can be designed. System is best suitable for various industrial and commercial applications along with domestic application.

8. References:

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