Design, Fabrication and Performance Analysis of Solar Cooker for Night Cooking

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Abstract: Solar cooking and water heating are widely accepted at domestic and commercial level as clean and green energy applications. Referring to the different collector designs, it has been concluded that cost wise box type cooker is better and Compound Parabolic Collector (CPC) is better when cooking time is considered. Hence it was planned to design, fabricate and analyze a type of cooker which is not subjected to tracking but can harness maximum solar energy throughout the day. From the analytical and experimental results, the energy produced is far above the energy required to cook 500 gm of rice. There is a noticeable difference between analytical and experimental values of oil temperature due to variation in analytical and measured solar radiation level. The CPC based solar cooker setup is tested for six consecutive days. The maximum oil temperature is noted to be 110°C. During off-sunshine hours, the oil temperature drop was around 35°C. Due to the inclement weather and inherent limitations, the system couldn’t attain maximum efficiency. It is observed that during afternoon, oil temperature rise is sufficient to cook rice and the oil temperature during late evening is sufficient for food warming.

Keywords: Compound Parabolic Collector, Oil Storage Tank, Energy Content, Cooking Time

Introduction:
The major source of energy is derived from fossil fuels. Due to the limited availability or depletion of these sources with time, balance between the demand and supply of energy seems to be degrading in the coming years. Moreover the fossil fuels are polluting in nature. In order to maintain a balance between demand and supply of energy, there is a need to exploit renewable sources to the maximum limit possible thereby providing a clean, eco-friendly source of energy.

The per capita average annual domestic electricity consumption in India in 2009 was 96 kWh in rural areas and 288 kWh in urban areas for those with access to electricity, in contrast to the worldwide per capita average of 2600 kWh and 6200 kWh in the European Union. India currently suffers from a major shortage of electricity generation capacity, even though it is the world’s fourth largest energy consumer after United States, China and Russia. Renewable energy accounts for approximately 12% of a total 200 GW of power generation capacity installed in India. Demand for power in India has been increasing due to the rising population, growing economy, and changing lifestyles. Despite substantial capacity additions, the power sector is still in shortage of energy. Peak demand shortage averages around 12%.

Nowadays, low and medium thermal applications of solar energy are popular due to simplicity of design and economical feasibility. Solar water heating, solar distillation, solar drying and solar cooking are some of the practical applications of solar energy.

Solar cookers:
A solar cooker, or solar oven, is a device which uses the energy of direct sunlight to heat, cook or pasteurize food or drink. Over the past many decades, a number of designs of solar cooker have been developed. The majority of solar cookers presently in use are relatively cheap, low-tech devices. Although solar cookers have been available for many years, there is continuing interest in their performance optimization.

The two designs of box type cookers have been tested. The first type has a painted black base and second type has a pained black with coal. These designs were examined under two modes of operations: at fixed position and on tracking system. The cooker at a fixed position had recorded thermal efficiencies ranging from 25.2% to a sharp peak of 53.8% at the maximum solar intensity of the day with an average overall efficiency around 32.3%. Whereas, cooker with black coal pained installed on a sun tracking system gave higher water and pot temperatures, and thermal efficiency ranged from 28% to 62.1% with an average overall efficiency around 43.8% [1]. The research work presents a hybrid solution to problems presented by box-type solar ovens in night and cloudy conditions. The developed hybrid solar oven is supplied with both electric and solar energy and can be used in early morning hours, on cloudy days, or when solar radiation decreases or disappears. The experimental results demonstrate that these ovens are suitable for home use in dry climates [2]. All concentrating solar cookers were found to provide adequate temperature needed for cooking. But the common problem of these systems is the need for frequent tracking, and standing in the sun while cooking. A cylindrical solar cooker with two axes sun tracking system has been designed and tested during different days. It showed that the cylindrical solar cooker system with two axes tracking can increase water temperature up to 90°C [3]. The design development and performance
characteristics of direct steam generation by non-tracking solar paraboloidal dish concentrating system has been studied. The performance of the concentrator is experimentally investigated with the water circulated as heat transfer fluid. The system is fabricated with high reflectivity aluminium foil sheet. The test results gave steam temperature of 215°C with conversion efficiency of 60-70% [4]. An experimental set up consisting of an array of photovoltaic panels, microprocessor based tracking System, cylindrical parabolic collector, insulated oil storage container and insulated pipe was taken up for techno-economic assessment of solar steam cooking system. An assessment of viability of such system is discussed and the payback period found to be 26 months [5].

The other research work proposes a hybrid solar cooking system where the solar energy is brought to the kitchen. The energy source is a combination of the solar thermal energy and the Liquefied Petroleum Gas (LPG) that is in common use in kitchens. There are three parameters that are controlled in order to maximize the energy transfer from the collector to the load viz. the fluid flow rate from collector to buffer, fluid flow rate from buffer to load and the diameter of the pipes. The entire system is modeled using the bond graph approach with seamless integration of the power flow in these domains. The modeled system is simulated and the results are validated experimentally [6]. The inventor reviews relevant issues on solar cooking in order to define and evaluate an innovative layout of a portable solar cooker of the standard concentrating parabolic type that incorporates a daily thermal storage utensil. This utensil is formed by two conventional coaxial cylindrical cooking pots, an internal one and a larger external one. The void space between the two coaxial pots is filled with a phase change material (PCM) forming an intermediate jacket. The numerical model is used to study its transient behavior for the climatic conditions and validated with experimental data. The results indicate that cooking the lunch for a family is possible simultaneously with heat storage along the day. Keeping afterwards the utensil inside an insulating box indoors allows cooking the dinner with the retained heat and also the next day breakfast. This expands the applicability of solar cooking and sustains the possibility of all the day around cooking using solar energy with a low inventory cost [7].

Another research work includes a self-circulating loop coupled with a heat storage and a solar parabolic trough. The loop is filled with thermal oil (Duratherm 630). Based on experimental results of the charging of a heat storage, a numerical upscaling of the system is made using Matlab. By numerically improving the coating of the absorber, modifying the pipe diameters and optimizing the size and the content of the storage, an optimal system can be virtually designed. The storage is originally based on aluminum cylinders filled with nitrate salts immersed in the heated oil coming from the self-circulating loop. The salts provide latent heat to the heat storage (melting temperature: 215 to 225°C). The absorber is originally insulated with an air layer; an evacuated tube is then numerically tested. The vacuum provides a much better insulation: it allows then a greater potential for heat storage. However, overheating of the oil in the absorber is an issue and the design of the pipes needs then to be modified (increase of diameter). A new heat storage based on tin is virtually designed, with larger heat storage potential. The diameters of the pipes are slightly increased again to speed up the flow and reduce overheating [8]. It has been concluded from the detailed literature review that the information pertaining to the application and analysis of low cost non-tracking type compound parabolic collector (CPC) trough for solar cooking is limited. Hence there is a need to get this topic into limelight.

**Design considerations:**
The prime intention was to fabricate a CPC solar cooking system which can harness maximum solar radiation throughout the day. Hence it had been decided to incorporate 3 troughs with different orientations without tracking. The various parameters to be considered in the design and performance analysis are discussed here.

**A. Energy requirement for cooking**
It has been observed that to cook 500gm of rice, approximately 0.28 kWh of energy is required [9]. The width (W) of the CPC can be calculated as:

\[ C = \frac{(W - D_o)}{\pi D_l} \]  

Absorbed solar flux is given by:

\[ S = \left[ I_0 R_p + \left( \frac{l_d}{C} \right) \right] \frac{\alpha}{\tau} \]  

Where, \( R_p \) is the tilt factor for beam radiation,

The intensity of radiation (at Manipal on 15th February) and the absorbed flux have been calculated analytically (as shown in Table 1) by referring to the specifications mentioned in Table 2. This is to ensure the effective working of the solar cooker. Useful heat gain by the system is:

\[ Q_u = F_p W L \left[ S - (U_L/C)(T_{hi} - T_a) \right] t \]  

\[ = m C_p (T_{ho} - T_{hi}) \]  

**Table 1: Solar radiation analysis with time**

<table>
<thead>
<tr>
<th>S.No.</th>
<th>Time interval (t) (h)</th>
<th>Beam radiation ((I_0)(W/m^2))</th>
<th>Diffused radiation ((I_d)(W/m^2))</th>
<th>Absorbed flux ((S)(W/m^2))</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10 - 11</td>
<td>751.87</td>
<td>102.48</td>
<td>499.84</td>
</tr>
<tr>
<td>2</td>
<td>11 - 12</td>
<td>861.92</td>
<td>104.59</td>
<td>547.27</td>
</tr>
<tr>
<td>3</td>
<td>12 - 13</td>
<td>899.45</td>
<td>105.22</td>
<td>567.34</td>
</tr>
<tr>
<td>4</td>
<td>13 - 14</td>
<td>861.92</td>
<td>104.59</td>
<td>547.27</td>
</tr>
<tr>
<td>5</td>
<td>14 - 15</td>
<td>751.87</td>
<td>102.48</td>
<td>499.84</td>
</tr>
</tbody>
</table>


Table 2: Specification of CPC [10]

<table>
<thead>
<tr>
<th>S. No.</th>
<th>Description</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>OD of the evacuated tube (D_o)</td>
<td>58 mm</td>
</tr>
<tr>
<td>2</td>
<td>ID of the evacuated tube (D_i)</td>
<td>48 mm</td>
</tr>
<tr>
<td>3</td>
<td>Length of the tube (L)</td>
<td>1800 mm</td>
</tr>
<tr>
<td>4</td>
<td>Transmissivity of cover material (τ)</td>
<td>1 (no cover)</td>
</tr>
<tr>
<td>5</td>
<td>Reflectivity of Aluminium Foil (α)</td>
<td>0.6</td>
</tr>
<tr>
<td>6</td>
<td>Absorptivity of the inner tube (α)</td>
<td>0.9</td>
</tr>
<tr>
<td>7</td>
<td>Collector heat removal factor (F_R)</td>
<td>0.95</td>
</tr>
<tr>
<td>8</td>
<td>Overall heat loss coefficient (U_L)</td>
<td>7.5</td>
</tr>
<tr>
<td>9</td>
<td>Concentration ratio (C)</td>
<td>1.6</td>
</tr>
</tbody>
</table>

Where, 'm' is the mass of oil in the container in kg, 'T_a', 'T_h', and 'T_ho' are the surrounding, oil inlet and outlet temperature respectively.

Initially a CPC trough was designed, fabricated and fitted with an evacuated tube and container. The used engine oil \((ρ = 850 \text{ kg/m}^3 \text{ and } C_p = 2395 \text{ J/kgK})\) of 5 litres was taken to evaluate the analytical (referring Eq. 4) and experimental final temperature as shown in Figure 1. The analytical (assuming adiabatic vessel) and experimental energy content of oil (effectively 1.75 litres) at 1430 hrs is calculated to be 0.144 kWh and 0.147 kWh respectively. Since both the values were closely matching and the total energy content from three troughs was more than the actual energy requirement, it had been decided to proceed with three troughs.

B. Modelling of CPC trough

By considering the above design parameters, CPC modelling is done using CATIA V5 R18 software. Steps involved in modelling the CPC trough are as follows:

(i) An involute of a circle having same diameter as that of evacuated tube i.e. 58mm is drawn.
(ii) Using concentration ratio value of 1.6, acceptance angle is calculated to be 40° approximately. The involute profile is trimmed to the required acceptance angle of 40°.
(iii) Two parabolas are now drawn taking the diametrical ends of the evacuated tube as the respective foci of the parabolas.
(iv) Parabolas are adjusted to maintain the width of the CPC trough at around 300mm as calculated during the design considerations.
(v) In the ‘Sheet Metal Design’ Workbench, the CPC profile is extruded after giving the required sheet thickness as shown in Figure 2.
(vi) The side covers with a hole of 58mm are then made in ‘Part Design’ workbench.

Fabrication details:

The various components to be fabricated are discussed here:

A. CPC trough

Galvanized Iron (GI) has been selected as the most economical material for the CPC Trough. Moreover, GI Sheets can be bented and welded easily. To further enhance the reflectivity of CPC, it has been decided to stick aluminium foils along the entire trough length. The CPC troughs and side covers are fabricated using a 24 gauge and 18 gauge sheet respectively. The surface area of the designed CPC is calculated to be 1m². The fabrication steps involved are as follows:

(i) The contour of the CPC profile is cut from an 18 gauge GI sheet.
(ii) A 24 gauge GI sheet of length 1700mm is cut and the desired contour/profile is obtained along the entire length.
(iii) Hole of 60mm diameter is punched in both the side covers.
(iv) The two side covers are then welded to the CPC trough.
(v) Aluminium Foil is now stuck to the CPC to increase the reflectivity.

B. Oil storage tank

The fabrication procedure for the oil storage tank is explained below:

(i) Three holes of diameter 52 mm (size of GI pipe) and a small hole to insert vacuum valve are made on to an outer container.
(ii) Three holes of 52 mm diameter are also made in middle container and after inserting GI pipes into it, these are welded together with outer container as shown in Figure 3.
(iii) A lid of diameter same as that of middle container is taken and a hole of 186 mm is made to fix the inner container (to hold the cooker). To
pour oil and to check the oil temperature provision is made within the lid.

(iv) The inner container is brazed to the lid and later the lid is brazed to middle container as shown in Figure 4.

(v) M-Seal is applied at the brazed portions in order to completely seal the joint. The portion above the lid is covered with thermocol to minimize the heat loss as shown in Figure 5.

(vi) The space between the outer and the middle container is evacuated using a vacuum pump and the valve is completely tightened. The passage between inner and middle container is evacuated using a vacuum pump and the valve is completely tightened. The gap between middle and outer container is evacuated to minimize heat loss from hot oil to surrounding.

C. CPC system

Three troughs with evacuated tube are assembled as a single unit using metal frame. The provision has been made for both system as well as trough orientation. Three GI pipes protruded from oil storage tank are connected to evacuated tubes by Neoprene hose pipes as shown in Figure 6. The complete CPC system is shown in Figure 7.

Experimental set up:

The experimental set up (Figure 8 and Figure 9) consists of a solar radiation recorder and thermometer to measure oil temperature. The system was kept facing south and both solar radiation and thermometer readings were taken for many days before putting the cooker into it.
Results and Discussion:
The setup was tested with solar cooker and the highest temperature of oil recorded was 110°C and it was dropped to 75°C during 1930 hours as shown in Figure 10. It has been found out that the time required for cooking 500 gm of rice was less than an hour during afternoon period. Whereas the temperature available wasn’t enough to cook rice during late evening. But this temperature is sufficient to warm up the food. This inefficient nature of the system have been diagnosed as follows:
(i) The complete experimentation period was partially cloudy.
(ii) Since the evacuation process wasn’t perfect, the outer container surface temperature was high.
(iii) Since the pipe size is bigger, the conduction heat loss from pipe wall to container wall was considerable.
(iv) Heat loss from the outer surface of hose pipe and outer container as they weren’t insulated.

Conclusion:
The following conclusions are drawn based on the analytical and experimental study:
(i) There is a noticeable difference between analytical and experimental values of oil temperature due variation in analytical and measured solar radiation level.
(ii) The CPC design and fabrication is good enough to cater to the need of cooking energy.
(iii) The present innovative non-tracking CPC system can absorb maximum amount of solar radiation throughout the day.
(iv) By redesigning the CPC system, the stored energy level can be raised.
(v) Even though the initial investment is high, such systems can be encouraged due to its clean and green nature.

References:


