Performance evaluation of compound parabolic concentrator with evacuated tube heat pipe

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Abstract. The keen interest of harvesting solar energy is increasing because of its clean, green and cheap nature. The pv modules collect the energy from the sun and produce electricity. The solar thermal collectors collect the solar energy in the form of heat. Compound parabolic concentrator is a type of solar thermal collector, which has a combined parabolic structure concentrating the solar radiation on a single line focus where the receiver tube is placed. The performance can be further increased by placing the evacuated tube, which traps the heat. The heat is efficiently conducted by using the heat pipe. A heat pipe is a heat-transfer device that transfer the heat between two solid interfaces. It combines the principles of both thermal conductivity and phase transition. The experimental study is carried out to find out the performance characteristics. The results according to the various parameters such as mass flow rate, tilting angles were plotted to find the better performance. The result shows that the maximum efficiency of the CPC is achieved between 12.00hrs. and 15.00hrs. The intensity of radiation during maximum efficiency is $10^00\text{ W/m}^2$ to $10^50\text{ W/m}^2$.

Keywords: Solar Energy, Compound Parabolic Concentrator, Evacuated Tube, Heat Pipe

1. Introduction

The sun’s energy is available in most of the place, which is used for the advancement of technology. The solar energy is harvested using PV modules and solar thermal collectors for domestic and industrial applications at temperatures of 60°C to 300°C [1]. Solar thermal collectors as well as Solar concentrators are the devices used for concentrating solar energy for various purposes such as Solar water treatment technologies based on CPC [2], air heaters using solar concentrators [3], solar cookers based on CPC [4], Water heaters based on solar collectors [5], steam generators based on CPC [6].

Solar thermal collectors use heat-absorbing panels to absorb sunlight directly. The solar collectors commonly refer to solar hot water panels, but may refer to installations such as parabolic troughs [7] and solar towers. Here the solar energy is directly used for heating purpose [8] and in large it can be used to produce steam that can run the generator to produce electricity [6]. The types of solar collectors are imaging and non-imaging types. The compound parabolic concentrator is a non-imaging type concentrator which has ability to concentrate rays to smaller absorber surface [10]. The sunray falling on the absorber is not focused, therefore concentration is achieved with a CPC design [11].

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The compound parabolic collector is a combined parabolic structure, which concentrates the solar radiation on a single line focus [12]. The rays falling on the CPC is reflected to a single line focus based on the “edge ray principle” [10]. They are called “non-imaging” because they do not produce any optical image of the source. Compound parabolic concentrators (CPCs) is designed as stationary solar collectors to achieve relatively high temperature operations with high cost effectiveness [13].

The light rays coming from the edges of the sources are redirected to the edges of the receiver. This confirms that all light rays coming from the inner points in the source will make contact with the receiver as shown in figure 1.

![Figure 1. Edge ray principle](image)

The rays falling on the CPC should be reflected to the receiver, so a reflective material is used which reflects the rays to the evacuated tubes. The reflective material should have high reflectivity.

Evacuated tube collectors are devices, which consists of cylindrical absorbing surface in which the vacuum is created between concentric glass tubes made up of borosilicate glass [16]. The outer layer is transparent allowing the light rays to pass through with minimal reflection. The inner layer is coated with a special selective coating (Al-N/Al) [17], which provides excellent solar radiation absorbing properties. The evacuated tube absorbs the solar energy reflected from the CPC and converts into the heat energy [18]. Thus, vacuum acts as an insulator, which does not lose the heat. To maintain vacuum between two glass layers a barium getter is used. This barium layer absorbs any CO, CO₂, N₂, O₂, H₂O and H₂ out-gassed from the evacuated tube during storage and operation, thus maintaining the vacuum.

A heat pipe is a heat-transfer device that transfer the heat between two solid interfaces. It works on both the principles thermal conductivity and phase transition [8]. Due to the very high heat transfer coefficients for boiling and condensation, heat pipes are highly effective thermal conductors. Therefore, when the heat pipe is introduced in the evacuated tube there would be more heat transfer resulting in a high efficiency solar thermal collector. Nano fluids can be used inside the heat pipe to increase the heat transfer [9]. The nano fluids such as CuO, graphene oxide nano fluids, etc. can be used inside the heat pipe [14].

2. Methodology

Description of various materials used and methodology used to make different parts detailed below.
2.1. Conceptual design
The conceptual design of CPC with evacuated tube was done with the SOLIDWORKS 3D modelling software shown in the figure 3.

Figure 2. Methodology

Figure 3. Conceptual design
2.2 Components

The components of the CPC are listed below

2.2.1 CPC The application of CPC is concentrating and illumination, the CPC is made by reflective material on its side wall. The base of the CPC is made of wood. The CPC dimensions were collected with the help of MATLAB statistical software and the truncation is done based on the experiment conducted by M.M. Isa [15], which results in the reduction of material size for economical purpose. The outline of the CPC is drawn on the plywood and is cut with the help of cutting wheel. The plywood acts as the supporter of the CPC and holds the Sheet metal, evacuated tube and heat pipe.

| CPC            | Specifications |
|----------------|----------------|
| Length         | 1500mm         |
| Aperture width | 341mm          |
| Surface area   | 0.96m²         |
| Material       | Plywood        |

The performance of CPC is increased with respect to the light intensity, which was proved by the experiment conducted by Ankur Geete. In addition, Giovanni casino tested CPC for larger acceptance angle (>30°) which shows better results depending on the solar intensity.

2.2.2 Evacuated tube The solar absorber tube has two concentric glass tubes closed at one end with an annular vacuum space and a selective surface absorber on the outer surface (vacuum side) of the inner tube. In heat pipe evacuated tube collectors, a sealed heat pipe, usually made of copper to increase the collector’s efficiency in cold temperatures, and is attached to a heat absorbing reflector plate within the vacuum sealed tube.

| Evacuated tube | Characteristics |
|----------------|-----------------|
| Length         | 1500mm          |
| Outer Diameter | 47mm            |
| Inner Diameter | 37mm            |
| Glass thickness| 1.6-2.0mm       |
| Material       | Borosilicate Glass |
| Absorbance     | Above 93%       |
| Emittance      | Above 8%        |
| Heat loss      | <0.8W/(m²°C)    |
| Startup temperature | <=25°C (77F) |
| No of coatings | 3               |
| Coatings       | Al/N/Al         |

2.2.3 Heat Pipe. The manufacturing of heat pipe involves selection of materials, cleaning process, checking for leaks, creating vacuum, and filling working fluid, instrumentation works and the testing of the heat pipe. The material selected for the heat pipe is copper because of its high thermal conductivity and it does not corrode. Also it has high melting point and copper allows heat to quickly pass through it. Therefore, it is used in quick heat transfer applications.

The cleaning of metal is necessary to remove any grease and impurities associated with the metal. The metal is placed in pool of hydrochloric acid and sodium-di-chromate. It will remove the grease and impurities. The copper tube is checked by allowing the helium inside the copper pipe. The flow of helium
shows any cracks and holes if any present in the copper pipe. There may be chances for micro cracks in the copper pipe which can be detected using helium.

Then the vacuum is created inside the copper tube with the help of vacuum pump. The vacuum pump sucks the air inside the copper pipe and maintains the pressure inside the copper pipe at 0.0004 bar. Then the acetone is filled inside the copper pipe to 40% of total volume. Then the pipe is sealed with the help of hydraulic press.

The thermocouple wires were fixed to the copper heat pipe to check the temperature at various points. The thermocouple wires were welded to the surface of copper heat pipe and sealed by silicon paste. Then the thermocouple wires are connected to the temperature indicator.

| Material               | Specifications |
|------------------------|----------------|
| Copper                 | Diameter       |
|                        | 19mm           |
|                        | Thickness      |
|                        | 1mm            |
|                        | Length         |
|                        | 1400mm         |
| Working fluid          | Acetone        |

The working fluid used here is Acetone which is colorless, volatile, flammable liquid. Its chemical formula is CH$_3$-CH$_3$-CO. The boiling point of acetone is about 56°C. The ph value of acetone is 7 i.e. neither acidic nor basic it is neutral. The acetone has excellent compatibility with copper and it has lower boiling point which is suitable for heat pipes.

2.2.4 Aluminium foil. The Aluminium foil is the reflective material used to reflect the falling radiation to the receiver tube. The reflectivity of the material is important and it shouldn’t absorb the falling radiation. The Foil is made of Al8011 type Aluminium material.

| Aluminium foil | Characteristics |
|----------------|-----------------|
| Reflectivity   | Above 85%       |
| Thickness      | 30 microns      |
| Surface area   | 0.96m$^2$       |

2.2.5 Condenser. The condenser is the important component of the setup. Condenser is attached to the heat pipe in which heat is transferred from the working fluid to the water. The working fluid in the heat pipe condenses and gives away its heat to the surrounding water and returns back to the evaporator region. The length of the condenser portion is 100mm and is made up of plastic pipe with one inlet and outlet tubes. The size of the inlet and outlet tube is 6.35mm.

2.3 Design calculations

2.3.1 Concentration angle. Concentration ratio = D/ (π*d)
Where, D = aperture area
      d = receiver diameter

2.3.2 Half acceptance angle. Half acceptance, $\phi = \text{arc sin} (1/C.R)$
2.4 Fabrication process
The fabrication process listed is done with the help of conventional machines available. The components and methods used to fabricate the components were discussed in the table.

| S.No. | Component name | Method of fabrication | Function |
|-------|----------------|------------------------|----------|
| 1     | Stand          | Cutting Drilling Welding Grinding | Provides support for the base and tanks |
| 2     | Base           | Cutting Drilling Screw joint | It holds the CPC and the evacuated tube |
| 3     | CPC            | Hand bending            | It reflects the solar radiation to the receiver tube |
| 4     | Heat pipe      | Cutting Welding Vacuum pumping Hydraulic sealing | It transfer the heat concentrated on the receiver to the condenser |
| 5     | Condenser      | Cutting Joining using silicon paste | In condenser the heat is transferred to the water flowing through it |

Mild steel pipes of size 1 inch were brought and cut using cutting wheel. Then the stand is made by welding the parts. Then the CPC structure were drawn on the plywood and cut using cut wheel. The sheet metal is placed over the plywood and screwed. The evacuated tube is placed on the CPC and hold with the help of clamp. The reflective material is fixed above the CPC. Then the heat pipe is placed inside the evacuated tube and the thermocouples were attached to the temperature indicator. The base of the CPC is placed above the stand and a screw rod is fixed to adjust the angle of the CPC.

2.5 Testing methodology

2.5.1 Mass flow rate. The various mass flow rates such as .016 kg/s, .025 kg/s, .033 kg/s, .041 kg/s, .05 kg/s were tested and the corresponding temperature were taken out. The water gets more heat when the mass flow rate is minimum. When the mass flow rate is maximum, the heat is transferred to more volume of water, which results in low temperature increase.

2.5.2 Tilting angle. The effect of a solar tilt angle on energy output may be up to 20% percent compared to flat plate collectors. Thus, various tilting angles like 10°, 15°, 20°, 30° and 45° and their corresponding results were plotted. The optimum tilting angle is based on the latitude and altitude of the location. The optimum angle for the Coimbatore is 11° facing south direction. This is the angle where the efficiency of the CPC is high.

The CPC is placed such that it facing south because that is generally where they would receive most sunlight. This is because India lies in northern hemisphere. Due to the tilt of the earth and elliptical orbit around the sun, the sun apparently moves from east to west from the south portion of the sky. Therefore, the roofs have high exposure to sun from the south direction.
3. Results and Discussions
The CPC was designed and fabricated as explained. The testing is done based on the testing methodology. Overall specifications with economic analysis, and test results found were detailed.

3.1 Experimental setup

![Experimental Setup of Compound parabolic concentrator with evacuated tube heat pipe](image)

Figure 4. Experimental Setup of Compound parabolic concentrator with evacuated tube heat pipe

3.2 Solar radiation intensity
The radiation intensity has a direct impact on the thermal efficiency of the CPC. If the radiation intensity is high, then the thermal efficiency of the CPC also high. The solar radiation intensity varies with the time. It increases steadily up to 14:00hrs and then decreases gradually. The performance of CPC is evaluated by exposing it to the indoor and outdoor conditions.

The CPC is placed to faces south. The CPC is kept at different tilting angles such as 0°, 11°, 30°, 45°. The temperature obtained at each tilting angle is noticed and the effective one is found. The solar radiation intensity varies with time. At first intensity is low which increases up to 14hrs and then it gradually decreases. The radiation intensity over the testing time period is explained below in figure 5. The efficiency of the CPC is increased greatly with the high intensity of radiation. The intensity of radiation is not constant. It differs each day due to atmospheric conditions. The maximum radiation intensity observed during the experiment was 1050W/m². The average intensity of radiation is about 933W/m².
The heat pipe requires some time to attain start up temperature. When heat pipe attains its start-up temperature, acetone evaporates and takes away the heat to the condenser portion. Acetone condenses and returns back to the evaporator portion. The phase change of liquid to vapor and vapor to liquid takes place in a cycle. The heat is transferred to the water flowing through the condenser portion. The heat absorbed by the heat pipe during the time is described in the figure 6. There are four thermocouples used which represents the temperature at various portions described in the table.

| Table 6. Representation of thermocouple |
|----------------------------------------|
| **Thermocouple No.** | **Indication**                      |
| T1                      | Atmospheric temperature             |
| T2                      | Temperature at end portion of heat pipe |
| T3                      | Temperature at middle portion of heat pipe |
| T4                      | Temperature of the condenser portion |

The evaporator and condenser portion of the heat pipe are attached with thermocouple. Thus the temperature indicator shows the temperature at various portions. The temperature was noted at a time interval of every two minutes then the water flow is done. Again changing the tilting angle, the reading was taken. This repeated throughout the experiment.

Assumptions made in the experiment

- The heat loss due to the clamp to hold evacuated tube was negligible
- The flow is constant throughout the experiment
- The intensity of tungsten halogen light is constant throughout the area
Figure 6. Temperature rise in heat pipe

3.3 Performance of CPC at varying tilting angles

The heat absorbed by the CPC at varying tilting angles like 0°, 11°, 30° and 45° are compared. The results show that increasing the tilting angle increases the efficiency of the CPC [19]. At high tilting angles the heat absorbed by the CPC increases up to 13:00hrs uniformly and then the efficiency decreases. At some angle the efficiency is nearly constant throughout the time period. Thus angle with constant efficiency throughout the day is chosen as optimum tilting angle. The results show that the optimum tilting angle is nearly 11° which is shown in figure 8. The CPC is facing towards south because this direction receives more heat throughout the day. The optimum tilting angle varies with the altitude. The efficiency can be increased by using tracking mechanism. The figure 7 represents the performance of CPC at tilting angle 0°.

The temperature of CPC is increased constantly up to 14:30hrs and then decreases. The figure 9 represents the performance of CPC at tilting angle 30°. At 30° the temperature increases steadily and then decrease after 14:00hrs. The reason for this is the sun moving towards the west the intensity of radiation falling on the CPC decreases. At 45° the temperature attains maximum value up to 14:00hrs. Then temperature drops rapidly. Because the radiation falling on the sun is minimum after 14:00hrs. The figure 10 represents the thermal performance of CPC at 45°.
Performance of CPC at 0° tilting angle

**Figure 7.** Thermal performance of CPC at 0° tilting angle
In the above chart, the CPC receives less heat at first and then the temperature of CPC increases to maximum value at 13:30hr and starts to drop. During 9:00 to 13:00hrs the efficiency is similar to other tilting angles. But after 13:00hr the efficiency of CPC is higher for 11°. Thus, the overall efficiency of CPC is high at the tilting angle 11°.

**Figure 8.** Thermal performance of CPC at 11° tilting angle
Figure 9. Thermal performance of CPC at 30° tilting angle

Figure 10. Thermal performance of CPC at 45° tilting angle
The experiment shows that at angle 11° the CPC receives heat throughout the experimental period and the overall efficiency is high for the whole day. The angles 30° and 45° shows the CPC receives more heat up to 14:00hrs and after 14:00hrs the heat absorbed by the CPC drops gradually. Thus optimum tilting angle for the compound parabolic concentrator thermal collector is 11°.

3.4 Thermal performance of CPC at indoor condition

The thermal performance of CPC at indoor condition was done which was represented in figure 11. The tungsten-halogen light acts as the light source for the CPC. The tungsten halogen light produces more heat and the radiation intensity of the tungsten halogen light is more than 2000W/m². The indoor testing does not produce the results obtained in the outdoor condition. The halogen light intensity can be varied by varying the supply voltage.

![Performance of CPC at indoor condition](image)

**Figure 11.** Performance of CPC at indoor condition

The experiment shows that the efficiency of the CPC can be increased with high reflectivity material. When the water flow is increased the temperature of the heat pipe drops suddenly. This is because the high volume of water takes away the heat, which results in low temperature rise. If the flow is very small, then the volume of water taking the heat is also small which results in high temperature of water. Thus, a very small flow of water is important to achieve the high temperature. In addition, the use of high reflective material increases the heat concentrated on the CPC, which further increases the efficiency of the CPC. The efficiency of the CPC can also be increased by attaching a solar tracking equipment. The solar tracking equipment tracks the solar radiation throughout the day and changes the direction of CPC to obtain maximum efficiency.
4. Conclusion
The testing of CPC results in improved performance, which resembles more energy, can be obtained using CPC. The additional setup of ray tracing technique further increases the performance of CPC. Because the ray tracing setup adjusts the CPC, such that the maximum rays can be utilized which results in higher concentration of rays. Thus, the efficiency is further increased. The results recommend using of CPC results in better efficiency, which can meet the energy demand increasing day to day. The efficiency of the CPC is also higher than other flat plate solar collectors.

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