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Experimental analysis of solar water heater with compound parabolic concentrator

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Abstract

Among all the non-conventional energy sources, solar energy is one of the most promising and renewable alternative source. Solar water heater can be one of the medium to make best use of this renewable energy for human betterment. The current work is targeted to examine the performance of solar water heater with different absorber plates viz flat plate, V-Trough and compound parabolic concentrator. The developed system is intended to supply hot water for a family at a low cost. This is regional study and illustrates how selecting a proper concentrator can increase the thermal efficiency of this solar based system. It was experimentally found that, the solar water heater with compound parabolic concentrator profile as absorber outshines over other two models giving 20.58% more efficient results than V Trough whereas V Trough gives us 20.37% more efficient results than Flat plate. Also, it is found that, less mass flow rate is required for obtaining higher degree of temperature in case of solar water heater with compound parabolic concentrator.

Keywords: Solar Radiation, Solar water heater, Passive system, parabolic collector

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1. Introduction

Solar energy is one form of non-conventional energy which is available free of cost and the simplest way of harnessing it is by directly converting it into useful thermal energy. A typical device that does the above conversion is a solar water heater (SWH). It heats up the heat transfer fluid such as water, non-freezing liquid or air for domestic usage [1]. Domestic water heating comprises 80-90% of heating load in India [2]. Hence, by using the sun as an energy source which is both renewable and free, we can cut the heating expenses by a large amount [3].

An extensive research has been done in the past [4-10] for SWH which depicts the deeper findings on the performance analysis of concentrating parabolic trough collector (CPC) as compared to the conventional flat plate collector based SWH. The research mainly focused on the circulation type, design and cost. Also, a detailed review and discussion about all the existing parabolic trough collectors was forwarded by Fernandez-Garcia et al. [11] that has been built till date and has been marketed in the past centuries. A review about its applications has also been given by them.

Pranesh et al. [12] reviewed the basic and applied research in compound parabolic concentrating solar thermal collector for domestic and industrial applications. The observations were focused on introducing new design concepts for industrial as well as domestic applications to

Nomenclature

θ_c = Half Acceptance angle	I_b = Hourly beam radiation
L = Length of the aperture/ receiver	I_d = Hourly diffuse radiation
w = width of the aperture	I_{bn} = Beam radiation in direction of rays
b = width of the receiver	I_T = The Total Radiation on Tilted Surface
C = Concentration Ratio	r_b = Beam Radiation
H = Height of Full CPC	r_d = Diffused Radiation
f = Focal length:	r_r = Reflected Radiation
θ_z = Zenith angle	ρ = reflectivity of the glass cover
γ = Surface Azimuth Angle	A = Area of Aperture
$\emptyset$ = Latitude angle	q_u = Useful Heat Gain
β = Slope angle	m = Mass flow rate
ω = Hour Angle	C_p = Specific heat of water
δ = Declination angle	T_o = Water outlet temperature
θ = Angle of Incidence	T_i = Water inlet temperature
Ig = Hourly global radiation	η = Efficiency

improve several aspects such as tracking mechanism, absorber temperature, material, selective cooling, annular gap, overall heat transfer coefficient, glazing etc. to reduce the cost of manufacturing. The sustainable growth in development of CPC solar collector progresses towards its betterment in efficiency and hence finds applications in various sectors worldwide.

Zhu et al. [13] configured stirling electric generators and integrated it with a parabolic trough collector. The set up was constructed and tested for solar thermal power generation in order to improvise the thermal losses and have an efficient solar thermal plant.

R. Subramanian et al. [14] performed comparative analysis of parabolic trough solar collector by varying absorber surface. The inline focus was given to parabolic trough collector under different conditions by varying the material of the absorber surface. Results were taken from parabolic trough collector for various collector setup it is found that more heat absorption is obtained by using Aluminium sheet.

Hadjiat et al. [15] carried a theoretical study to predict the thermal behavior of a novel SWH with CPC reflectors. A new design of an integrated collector storage was presented. The target is to reduce the size of the system and therefore minimize its cost and weight while keeping its optical and thermal performance which makes the system applicable for home use along the year.

Numerical and experimental investigation was performed by Yuan et al. [16]. The two collectors are identical except that one collector is equipped with a transparent Ethylene tetrafluoroethylene (ETFE) foil and the other collector is not. The results show that the CFD model predicts satisfactorily temperature rises of the collectors in the temperature range between 20 °C and 81 °C.

Based on the literature review, the present work is modeled to discuss about the performance analysis of CPC collector and further have a comparative analysis of solar water heater with Flat Plate, V-Trough and CPC collector in order to have a thermally more efficient solar water heater system.

2. Details of Model Fabricated

Many types of concentrating collectors are used for the maximum absorption of solar radiation. The schematic view of the experimental set up is shown in Fig 1 and contains the solar collector, storage tank, connecting pipe system and sensors. For the present experiment, three different collectors are used for the comparative analysis viz. compound parabolic concentrator, V-trough collector and flat plate collector and the details are discussed in below section.

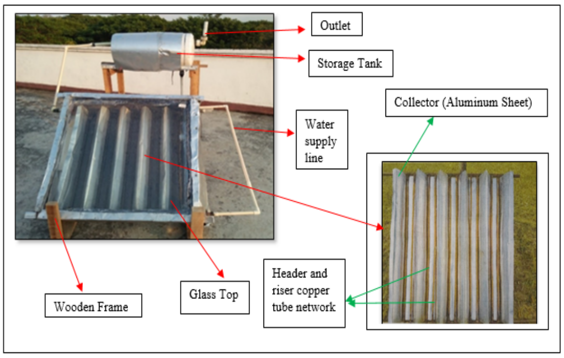

Figure 1. Experimental Setup

A header and riser copper tube network is placed (as shown in Fig. 1) inside the solar collector for the flow of fluid inside the collector. Copper pipes of diameter 12.7 mm were used as Riser tubes and diameter 25.4 mm were used as Header tubes. The copper tubes were first straightened and then welded to the header pipes. It is then covered with transparent glass.

2.1 Compound Parabolic Concentric Collector

A Compound parabolic concentrator (CPC) which is a type of non-imaging type concentrating solar collector is used in the current work. It is made using Winston's Profile as shown in Fig 2. The constructional feature in this case is that the two parabolic segments are oriented in such a way that the focus of one is located at the bottom end of the other parabola and vice versa. It can concentrate radiation on to linear receivers of small transverse width even if it receives radiation arriving with larger angular spread as depicted in Fig 3. This is one of the major advantages of CPC. Also, no tracking is required if the collector is placed in east-west direction.

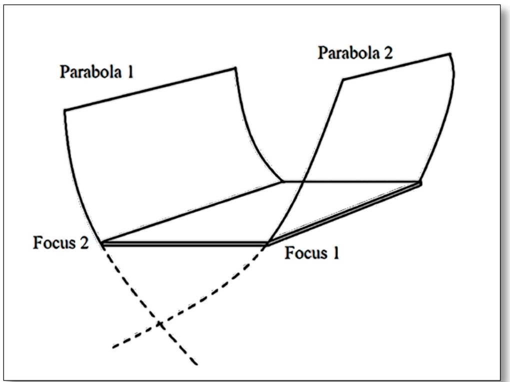

Figure 2. Winston's Profile (CPC) [17]

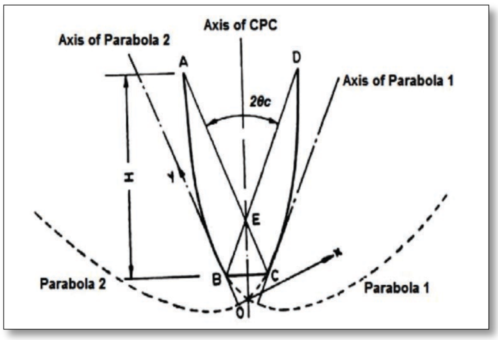

Figure 3. Geometry of CPC [18]

The profile of CPC is made using the geometry of Figure 3. The length of aperture (length of AD) and receiver (length of BC) are both made of same dimension.

Length of the receiver, L = 1 m

Width of the receiver, b = 0.06 m

Width of the aperture, w = 0.11 m

The concentration ratio is the system's ability to concentrate solar energy and is calculated by using geometry

$C=\frac{w}{b}=1.833$ …………………………………… (1)

The acceptance angle is the maximum angular opening that will allow the radiation from the sun to be trapped through the aperture width and get concentrated on the absorber width. It is calculated using Fermat's Principle,

$C=\frac{1}{\sin\theta c}$ ………………………………………..(2) $\theta_c = 33.06°$

Height and focus of the CPC were calculated using the formulae given by Rabl et al. [8]

$H = \frac{w}{2}(1+\frac{1}{\sin\theta c})\cos\theta_c = 130.59$ mm……............ (3)

$f=\frac{b}{2}(1+\sin\theta_c)=46.37$mm……………………..... (4)

Testing of Compound Parabolic Concentrator design

The collector was tested by placing it in a darkened room and making a beam of light incident on it. After reflection, the beam of light passed through the focus of the parabola affirming the correct design of the profile. The collector was then covered with glass and kept inside an aluminum box. The actual and the fabricated model of CPC are shown in figure 4 and 5.

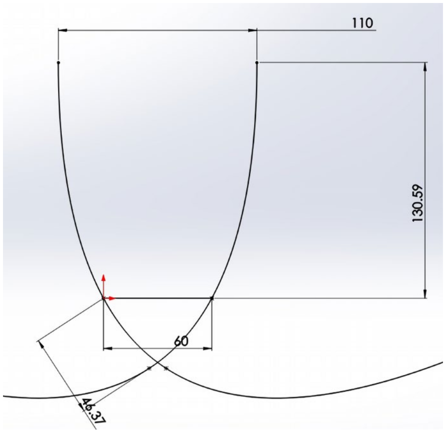

Figure 4. The actual CPC with dimensions (All dimensions are in mm)

Figure 5. The fabricated CPC

2.2 V-Trough Collector

The deciding factor for making a V-Trough collector was the V-Trough angle.

Calculation on March 21 at 0730 IST

Snce the collector is facing south, therefore surface azimuth angle, γ=0˚……………….……………………….…(5)

$\delta = 23.45 \sin\left[\frac{360}{365}(284+81)\right]$ …….……….. (6)

Latitude angle,φ=26.65˚ ………………………. (7)

Slope angle, $\beta = \varphi$ + 15˚= 41.65˚ ……………. (8)

Local Apparent Time = Standard Time ± 4(Standard time longitude –longitude of location) + (Equation of time correction) ………………... (9)

Therefore, Local apparent time = 0805

Hour angle,ω=58.75˚..……………………….. (10)

Now, V-trough angle θ can be calculated as-

$$\cos\theta = \sin\varphi\,(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) + \cos\varphi\,(\cos\delta\cos\beta\cos\omega - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta \quad \ldots(11)$$

Hence, for the V-trough system to work from 7.30AM on March 21, the V-trough angle is found to be 60°. Aluminum sheet is used and is given the V shape as shown in Fig 6 using V-Trough angle. The absorber area is painted in black for better absorption of radiation and then covered with glass and kept inside an aluminum box.

Figure 6. V Trough collector

2.3 Flat Plate Collector

For Flat plate collector, plain aluminum sheet was used. The sheet was painted in black for better absorption of radiation. It is then covered with glass and kept inside an aluminum box.

2.4 Selection of Materials and Design Specifications

Materials used for different purposes and their dimensions are taken as per IS 12933 (part-2).

Pipes- Copper pipes of diameter ½ inch and $^{7}/_{8}$ inch are used as riser tubes and header tubes respectively. Riser pipes are brazed to the header pipes and the whole arrangement is connected to the V-trough absorber plate.

Frame- The frame holds the casing (surrounds the absorber plate, tubes etc.) and the storage tank and keep them free from dust or moisture. It also acts as a base for the whole set up. The casing and frame both are constructed from Aluminum.

Absorber Plate-Taking into account the availability and low cost, aluminum sheet is opted as absorber plate. It has good thermal conductivity. Riser and header tube set up is then fitted to the fabricated absorber plate and then finally painted black in the receiver area to have better absorptivity.

Collector Insulation- The collector must be well insulated to reduce the conduction and convection losses which may take place mainly through the backside and the sides of the casing. Proper insulation is maintained so as to avoid such heat losses in the system.

Storage Tank- A Cylindrical Storage Tank was made which has second smallest area/volume ratio after sphere. Area/volume ratio is taken into consideration because heat loss is directly proportional to area. GI sheet is used to construct the tank and further is insulated using thermocole and sponges for better heat retention. Finally, it is sealed with polythene to make it waterproof. The final tank is shown in Fig 7.

Figure 7. Storage tank

The diameter and height of the tank is 0.26 m and 0.46 m respectively which can be obtained as follows-

Capacity of the storage tank = 0.025 m^3

Let L= 1.76 D

∴ Volume of storage tank (V) = Area × Length= $\frac{\pi}{4}D^2L$ ………………………………………… (12)

Sensors used- Three types of sensor are used during the experiment. The sensors were connected to Arduino Board to get the required output.
The sensors used along with their specifications are:

1. DS18B20 Temperature Sensor –
   This sensor is used to measure the temperature of the water.Two sensors of this kind are used in the present work. One for measuring the ambient temperature and the other for measuring the inlet temperature.
   Measuring Range: -55°C to 125°C
   Model: DS18B20 Temperature Sensor
   Type: Temperature Sensor and Controller

2. Digital Thermometer-
   This sensor is also used to measure the temperature of water. And this used sensor is used to measure the temperature of outlet water.
   Measuring Range: -55°C to 100°C
   Model: PM-10 (Wired with Probe)
   Type: Digital

3. Plastic Helical Rotor Flow Sensor-
   This sensor is used to measure the volume flow rate of the collector. This volume flow rate is converted into mass flow rate using an Arduino Board.
   Measuring Range: 10-1500 LPH
   Model: YF-S403 Water flow meter sensor
   Type: Electronic Component

2.5 Dimension and Material used

The low cost experimental set-up is designed and fabricated and the detailed listing in given in table 1.

Table 1. Dimensions and materials for experimental set-up

Units	Dimensions	Material Used
CPC Collector	Length of the receiver, L = 1 m Width of the receiver, b = 0.06 m Width of the aperture, w = 0.11m Concentration Ratio, C = 1.833 Acceptance Angle, θ_c = 33.06° Height of CPC, H = 0.13059 m Focal length, f = 0.04637 m	Stainless Steel Sheet, Aluminum Sheet, Thermocol e, Cardboard, Glass.
V Trough Collector	Length = 1 m Breadth = 1 m Thickness = 0.0007 mm Angle of the V = 60^O	Aluminum Sheet, Glass.
Flat Plate Collector	Length = 1 m Breadth =1 m Thickness = 0.0007 m	Aluminum Sheet, Glass.
Storage Tank	Diameter = 0.26m Length = 0.46 m Capacity = 0.025 m^3	GI Sheet, Thermocol e, Sponge.
Header and Riser Tube Network	Header tube diameter = 0.0254 m Riser tube diameter = 0.0127 m	Copper tube

3. Experimental Procedure

The comparative analysis is studied taking three collectors as absorber viz compound parabolic concentrator, V-trough collector and flat plate collector into consideration. The experiments for all the three cases are conducted for repetitive times (5 to 6 times to ensure the accuracy of the readings) and for similar environmental conditions i.e. rainy, foggy and sunny days and data are stored with the help of sensors as discussed in section 2.4.

3.1 Principle of Operation

A solar collector is a device which is used to collect the sun's radiation as heat and then transfer this collected heat to the fluid passing in contact through the collector. A solar water heater uses water as the circulating fluid. This fluid can be circulated using two methods namely passive and active. In passive method natural circulation is used which is also known as Thermosiphon principle whereas in active method pumps are used. As Natural Circulation is more economic, this method is used in the present study.

The DS18B20 Temperature Sensor is fixed on the pipe that connects the storage tank and the bottom header tube of the solar collector to calculate the inlet temperature of water. Water coming from the tank flows into the absorber (as referred to Fig 1) and gains heat thus becoming less dense. On the principle of Thermosiphon, hot water rises up to the storage tank. The PM-10 Digital Thermometer is connected between the top header tube and storage tank. As hot water passes through the sensor, outlet temperature is observed. Also in the storage tank, the hot water because of its less density occupies the upper portion of the tank and simultaneously cold water occupies the lower portion of the tank which ultimately flows to the copper tubes due to gravity. Thus the circulation continues as cold water comes in, while the hot water goes out from the tank again by following Thermosiphon principle.

3.2 Efficiency calculation

The performance of all the collectors is measured in terms of efficiency and is calculated having various solar angles as discussed as below. With the help of Solar Radiation Geometry, the angles associated with it were calculated. Since the experiment was conducted at Tezpur University, the latitude angle is taken to be the latitude of Tezpur. Therefore, $\emptyset = 26.65°$ ……..(13)

The collector was placed facing south, therefore, Surface Azimuth Angle (γ) = 0°…….…..…… (14)

With the help of latitude angle, Tilt angle is calculated as $\beta = \varphi + 15°$……………….…… (15)

The experiment was conducted from 08:00 hours to18:00 hours with observations taken after every 15 minutes. So, the hour angle (ω) differed and was calculated for every time the observations were taken.

Again, the experiments were conducted on different days and so the Declination angle (δ) was calculated for each day with the formula,

$\delta = 23.45 \sin\left[\frac{360}{365}(284+n)\right]$, where n is the day of the year…………………………………. (16)

The Incidence Angle (θ) and Zenith angle (θ_z) differed for each collector, for every specific day and for every time the observations were taken. They are calculated as:

$$\cos\theta = \sin\varphi\,(\sin\delta\cos\beta + \cos\delta\cos\gamma\cos\omega\sin\beta) + \cos\varphi\,(\cos\delta\cos\beta\cos\omega - \sin\delta\cos\gamma\sin\beta) + \cos\delta\sin\gamma\sin\omega\sin\beta \quad \ldots\ldots(17)$$

And $\cos\theta_z = \sin\delta\sin\emptyset + \cos\delta\cos\emptyset\cos w$ …... (18)

The Total Radiation on Tilted Surface (I_T) was also calculated for each collector, for every specific day and for every time the observations were taken. They are calculated using the formulae given by ASHRAE. The formula used are as follows.

$$I_{bn} = A\exp\left[-\frac{B}{\cos\theta_z}\right] \quad \ldots(19)$$

$$I_b = I_{bn}\cos\theta_z \quad \ldots(20)$$

$$I_d = C\,I_{bn} \quad \ldots(21)$$

$$I_g = I_b + I_d \quad \ldots(22)$$

Where, A, B and C are constants whose values are determined on month wise basis.

$$r_b = \frac{1+\sin\delta\sin(\varphi-\beta)+\cos\delta\cos\omega\cos(\varphi-\beta)\cos\beta}{0.475} = \frac{\cos\theta}{\cos\theta_z} \quad \ldots(23)$$

$$r_d = \frac{1+\cos\beta}{2} \quad \ldots(24)$$

$$r_r = \frac{\rho(1-\cos\beta)}{2} \quad \ldots(25)$$

$$I_T = I_b r_b + I_d r_d + (I_b + I_d) r_r \quad \ldots(26)$$

The overall efficiency of the collector is calculated as

$$\eta = \frac{q_u}{A I_t} \quad \ldots(27)$$

Where, $q_u = mC_p(T_o - T_i)$…………………….. (28)

4. Results and Discussion

The experiments are conducted for similar environmental conditions for all the absorbers. The water inlet and outlet temperatures are noted for all the experiments and are depicted in the form of graphs as discussed below.

4.1 V-Trough Collector

The experiments were conducted for two environmental conditions i.e. foggy and sunny days and the set-up (as explained in section 2) is shown in Fig 8.

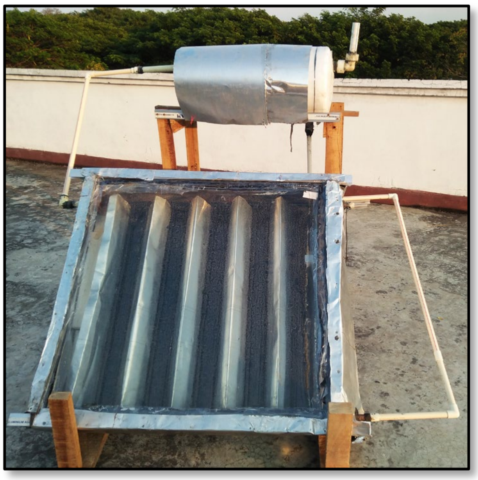

Figure 8. Setup of V-Trough SWH

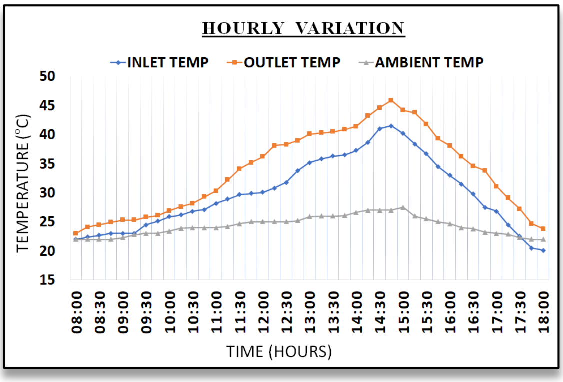

Figure 9. Temp vs Time values observed on a foggy day

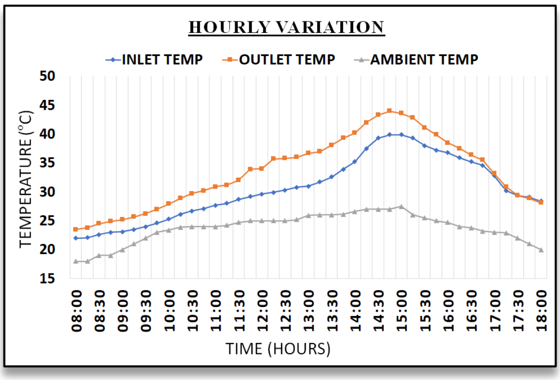

Figure 10. Temp vs Time values observed on foggy day with sunny afternoon

Figure 9 shows the data collected on a foggy day with maximum ambient temperature as 27.5ºC. It is seen that a maximum of 45.9ºC outlet temperature is obtained and a maximum of 41.5ºC storage tank water temperature is obtained at 14:45 hours of this day.
Figure 10 shows the data collected on a sunny day. So, the maximum ambient temperature observed was 27.5ºC. It is seen that a maximum of 44ºC outlet temperature is obtained and a maximum of 39.9ºC storage tank water temperature is obtained at 14:45 hours of this day.

4.2 Flat Plate Collector

The experiments were conducted for two environmental conditions i.e. foggy and sunny days and the set-up is shown in Fig 11.

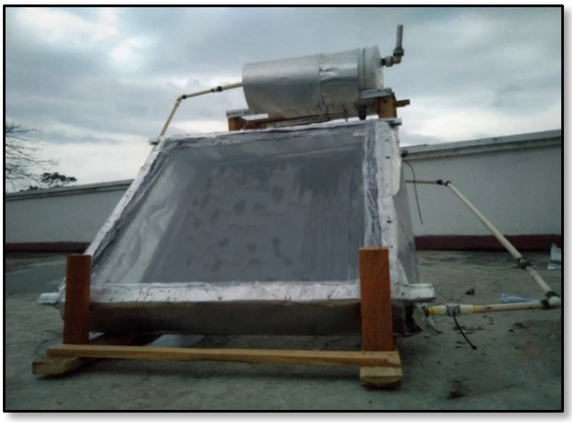

Figure 11. Setup of Flat plate SWH

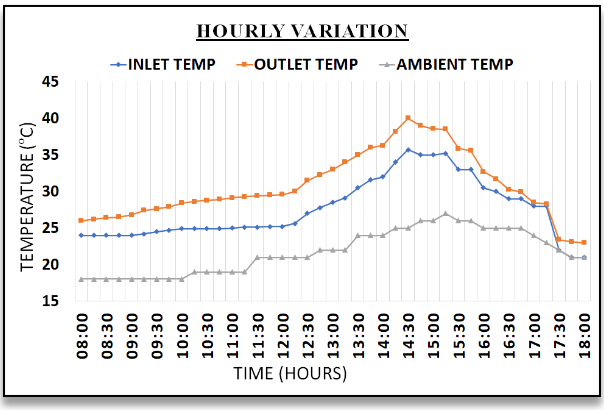

Figure 12. Temp vs Time values on a foggy day

Figure 12 shows the data collected on a foggy day. It was slightly cozy day during the morning and evening period. So, the maximum ambient temperature observed was 27ºC. It is seen that a maximum of 36.7ºC outlet temperature is obtained and a maximum of 33.5ºC storage tank water temperature is obtained at 14:15 hours of this day.

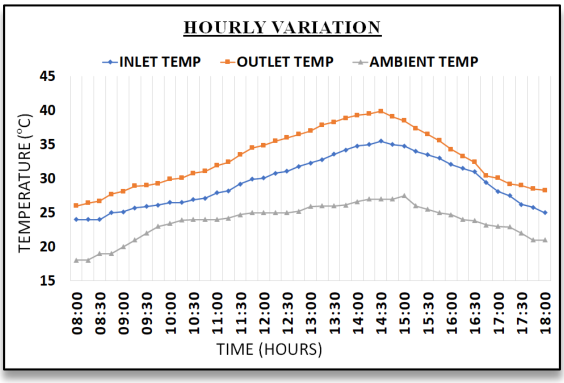

Figure 13. Temp vs Time values observed on a foggy day with sunny day

Figure 13 shows the data collected on a foggy day. It was quite foggy in the morning and evening but sunny during the afternoon. This day was quite similar to the day on which the V Trough experiment was conducted. So, the maximum ambient temperature observed was 27.5ºC. It is seen that a maximum of 39.9ºC outlet temperature is obtained and a maximum of 35.5ºC storage tank water temperature is obtained at 14:30 hours of this day.

4.3 CPC Collector

The experiments were conducted for three environmental conditions i.e. foggy, sunny and rainy days and the set-up is shown in Fig 14.

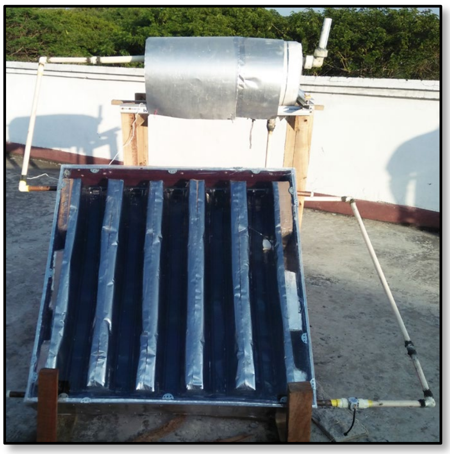

Figure 14. Setup of CPC SWH

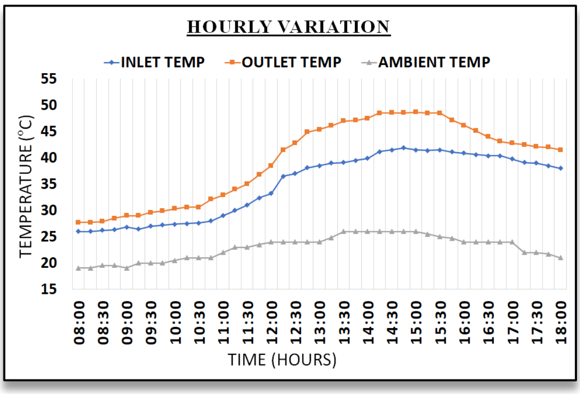

Figure 15. Temp vs Time values observed on a foggy day

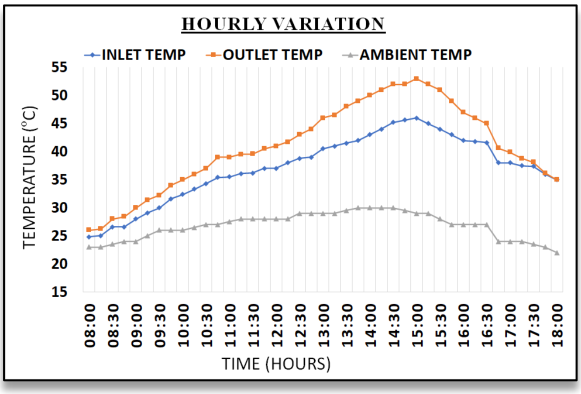

Figure 16. Temp vs Time values observed on a foggy day with sunny day

Figure 15 shows the data collected on a foggy day. It was quite foggy day. This day was quite similar to the day on which the V Trough experiment and flat plate experiment was conducted. So, the maximum ambient temperature observed was 26^{O}C. It is seen that a maximum of 48.7^{O}C outlet temperature is obtained and a maximum of 41.9^{O}C storage tank water temperature is obtained at 14:45 hours of this day.

Figure 16 shows the data collected on a sunny day during the month of April. So, the maximum ambient temperature observed was 30^{O}C. It is seen that a maximum of 53^{O}C outlet temperature is obtained and a maximum of 46^{O}C storage tank water temperature is obtained at 15:00 hours of this day.

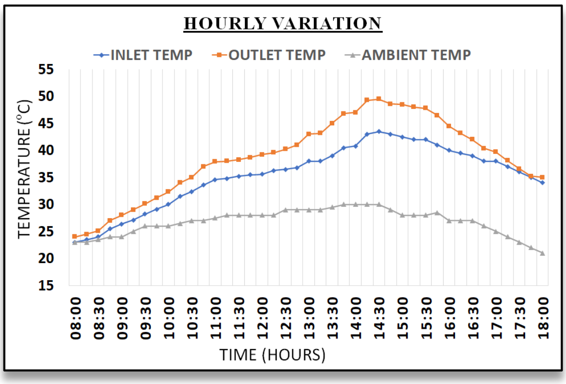

Figure 17. Temp vs Time values observed as on rainy day

Figure 17 shows the data collected on a rainy day during the month of April. Though it was raining heavily but the weather was quite hot that day. So, the maximum ambient temperature observed was 30^{O}C. It is seen that a maximum of 49.5^{O}C outlet temperature is obtained and a maximum of 43.5^{O}C storage tank water temperature is obtained at 14:30 hours of this day.

4.4 Performance Results

The comparative performance graph is depicted in Fig 19. The data is collected for similar environmental conditions.

Efficiency-Time Graph

Figure 18 shows the data plotted between the Efficiency versus Time values calculated for the Flat Plate, V Trough and CPC Collector.

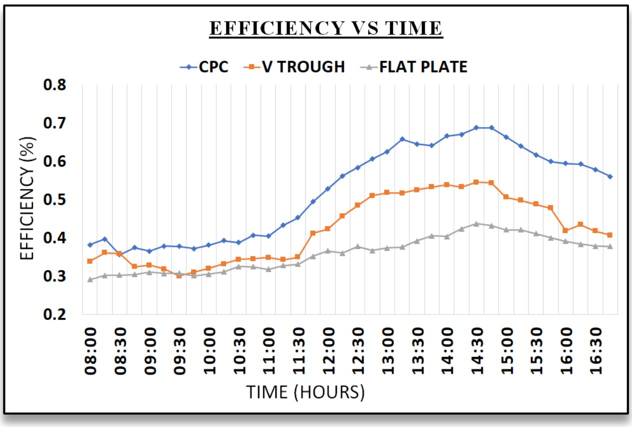

Figure 18. Efficiency vs Time values observed for the Flat plate, V Trough and CPC Collector

The above graph shows a maximum of 68% efficiency for CPC whereas 54% and 43% for V trough and Flat plate respectively.

Inlet Temp – Time Graph

Figure 19 shows the data plotted between the Inlet Temperature versus Time values calculated for the Flat Plate, V Trough and CPC Collector.

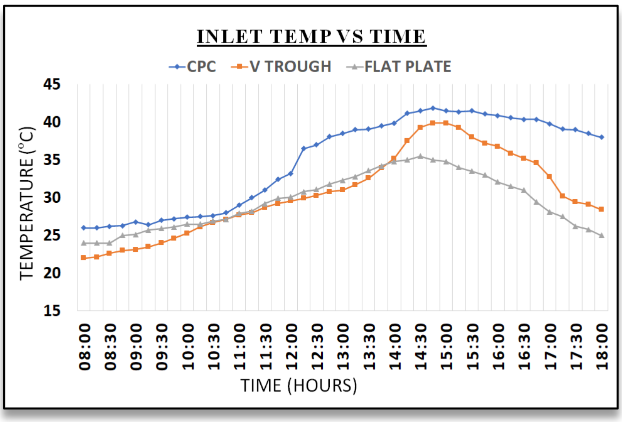

Figure 19. Inlet Temp. vs Time values observed for the Flat plate, V Trough and CPC Collector

The above graph shows temperature variation between the inlet temperatures of three collectors. Maximum inlet temperature is found to be obtained in case of compound parabolic collector.

Outlet Temp – Time Graph

Figure 20 shows the data plotted between the Outlet Temperature versus Time values calculated for the Flat Plate, V Trough and CPC Collector.

The graph shows temperature variation between the outlet temperatures of three collectors. Maximum outlet temperature is found to be obtained in case

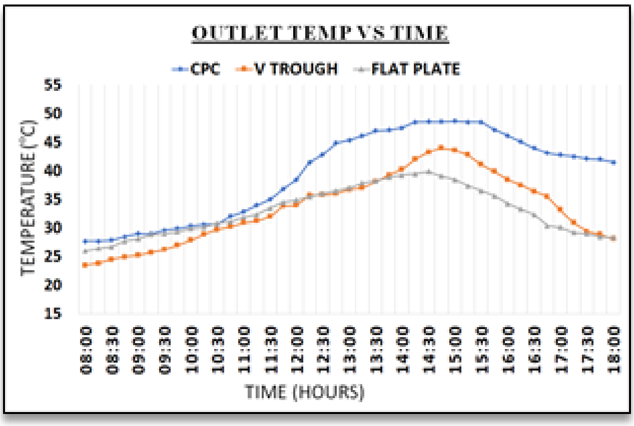

Figure 20. Outlet Temp. vs Time values observed for the Flat plate, V Trough and CPC Collector

of compound parabolic collector. The peak temperature values are shown in table 2.

Table 2. Comparative Analysis of Flat Plate, V-Trough and Compound Parabolic Concentrator based Solar Water Heater

Collector Type	Inlet T(°C)	Outlet T.(°C)	Ambient T.(°C)	$\dot{m}$(Kg/Sec)	η(%)
Flat Plate	35.5	39.9	27	0.0196	43.73
V Trough	39.3	43.3	27	0.0178	54.61
CPC	41.5	48.6	27	0.0107	68.86

The table 2 shows the data obtained by conducting the experiment for the Solar Water Heater with flat plate, V-Trough and CPC collectors. The data shown are for the days on which they show maximum similar environmental conditions. The table shows the data for which the maximum efficiency is obtained. It can be observed that with the decrease in mass flow rate, the efficiency increases. As mass flow rate decreases, the density decreases. Hot water has less density and thus it can be seen that with CPC collector, the mass flow rate decreases thus heating the water faster. This can be attributed by the fact that, the geometrical arrangement of CPC assists the collection of solar radiation entering the collector aperture within the acceptance angle which enables it to operate without continuous tracking.

5. Conclusion

The following conclusions from the present experimental work can be made:

1. From the graphs, it is clear that the highest efficiency is obtained in the CPC collector and then from the V trough and lastly from the flat plate. CPC gives us 20.58% more efficient results than V Trough whereas V Trough gives us 20.37% more efficient results than Flat plate. Thus, it can be seen that the CPC collector is more efficient than the V Trough and flat plate collector. It was already theoretically proven, but this experimental analysis made it more clearly with the values obtained.
2. It is also observed with the comparative analysis that, the solar water heater with compound parabolic concentrator as absorber needs less mass flow rate and provide higher degree of water temperature as compared to the other two models which makes it a suitable design to operate with large volume of water, applications such as swimming pools, hotels etc.

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