Educational Administration: Theory and Practice
2024,30(2), 347-352
ISSN:2148-2403
https://kuey.net/

Research Article

Performance Analysis Of Solar Water Heater With Compound Parabolic Collector

Vipul Patel[1]*, Bhargav Patel[1], Rakesh Oza[1]

[1]Assistant Professor, Mechanical Department Government Engineering College, Patan.

***Corresponding author:** Vipul Patel
Email: vkpatel.gec@gmail.com

Citation: Vipul Patel et al. (2024), Performance Analysis Of Solar Water Heater With Compound Parabolic Collector, *Educational Administration: Theory and Practice*, *30*(2), 347-352,
Doi: 10.53555/kuey.v30i2.1297

ARTICLE INFO

Accepted: 29 Mar 2024

ABSTRACT

Solar thermal technology is most commonly used for water heating and power generation in sunny climates. However, The auxiliary necessity of a solar water heating system affects its cost and viability for the end user. Due to the complex design, production and maintenance costs, systems based on solar thermal have fallen behind in alternative energy systems. The concentrated solar thermal energy system is based on the traditional design of a parabolic concentrator, with the receiver located along the line connecting the concentrator's centre to the sun. This makes it possible for the efficient collection and concentration of incoming solar irradiation. By focusing on the incoming radiation, the system's operational temperature is greatly enhanced, which improves the efficiency of the cool-to-hot water conversion. Compound parabolic collector used with 96% concentration ratio in the present work. Theoretically able to produce temperatures up to 71°c. However, due to optics deterioration and other variables, temperatures 60°c have been reached. Parabolic Collector has achieved 62% efficiency.

Keywords: Solar radiation, Compound parabolic collector (CPC), Water Heater, Collector.

1. Introduction

The rising expense of fossil fuels and power, combined with environmental concerns from CO2 emissions, has sparked interest in renewable energy. Even in today's global marketplace, with all of the huge technological breakthroughs and improvements, some people still live in darkness at night and study with candlelight or gasoline lights. These people are aware that electricity exists; nevertheless, the location in which they live lacks the necessary infrastructure and funds for such a service. Furthermore, the global demand for usable energy is constantly increasing, with electricity emerging as the preferred energy source. This electricity creation, however, is not free. The infrastructure required to establish new power-generating plants is costly, as is the rising cost and scarcity of fossil fuels. There are technologies obtainable for heating water, air heating, drying, space heating, cooling, and electricity generation In 2011, the global total capacity of solar water heating systems reached 160 GW to 185 GW[1].

Residential water heating accounts for 80%-90% of India's heating load [2]. Another option is to abandon traditional ways in favor of new, alternative, sustainable energy sources, such as solar energy. The sun is a great source of radiant energy and the globe's largest source of energy. It emits electromagnetic radiation with an average irradiance of 1367 W/m² on the earth's surface[2]. Solar thermal collectors convert the sun's energy into heat, which can then be stored in water for ideal utilization[3]. To maximize solar radiation absorption, many different types of concentrating collectors are used.[4], [5]:

(i) Compound parabolic collector (CPC),
(ii) Parabolic trough collector (PTC),
(iii) Linear Fresnel collector (LFC), and
(iv) Central receiving system (CRS)/power tower.

The most popular permanent solar collectors are evacuated tube and flat-plate collectors Improving the effectiveness of a solar thermal collector involves using high-efficiency heat exchange absorbers and increasing solar radiation concentration[6]. Previous studies on solar water heaters have shown that concentrating parabolic trough collectors (CPC) is superior to traditional flat plate collectors[1], [3], [6], [7]The findings concentrated on presenting novel designs for industrial and domestic applications to enhance multiple factors such as tracking mechanism, absorber temperature, material, specific cooling, annular gap, overall heat transfer coefficient, glazing, and so on, in order to reduce production costs. The continued improvement of CPC solar collectors leads to increased efficiency and, as a result, applicability in a variety of sectors around the world[8], [9], [10]. The low concentration ratio reduces the tracking need, and many CPC systems can run without tracking, leading to lower costs[11], [12]. A CPC's geometric design depends on its application, and manufacturers consider operating conditions in each scenario. An important feature within the design is the relationship between the concentration ratio and the rate of acceptance angle, which is reversed[13]. A comparison of stationary and tracking CPCs showed that tracking enhances efficiency by around 15%[14].

In this study, a non-imaging compound parabolic concentrator (CPC) is used to concentrate solar energy. Develop CPC design and evaluate its working characteristics and thermal performance under various weather conditions, highlighting its qualities.

2. Experimental Model

Nomenclature for solar thermal system	
θa = Half Acceptance angle	L = Length of the aperture/ receiver
δ = Declination angle	w = width of the aperture
f = Focal length	b = width of the receiver
θz = Zenith angle	H = Height of Full CPC
γ = Surface Azimuth Angle	C = Concentration Ratio
∅ = Latitude angle	Ig = Hourly global radiation
β = Slope angle	Ib = Hourly beam radiation
ω = Hour Angle	Id = Hourly diffuse radiation
θ = Angle of Incidence	Ibn = Beam radiation in the direction of rays
qu = Useful Heat Gain	IT = The Total Radiation on Tilted Surface
m = Mass flow rate	rb = Beam Radiation
Cp = Specific heat of water	rd = Diffused Radiation
Tfo = Water outlet temperature	rr = Reflected Radiation
Tfi = Water inlet temperature	ρ = reflectivity of the glass cover
η = Efficiency	A = Area of Aperture
LST = Local Solar Time	

2.1 Design of CPC

CPC is produced using Winston's Profile, as illustrated in Figure 1. The constructional peculiarity in this study is that the two parabolic segments are placed so that the focal point of one is at the bottom of the other, and vice versa. There are four important terms related to CPC: aperture width(w), concentration ratio(c), acceptance angle(2θa) and absorber width(b). The concentrator is formed up of two sections, parabolas 1 and 2. The two parabolas' axes form an angle so that the lower point of parabola 2 is the concentration of parabola 1 and the lower point of parabola 1 is the concentration of parabola 2 is called the acceptance angle (2θa). The concentration ratio is calculated by equation 1[15].

$$C = \left(\frac{W}{B}\right) = \left(\frac{1}{Sin\theta_a}\right) ------ (1)$$

This concentration ratio indicates the greatest feasible for the acceptance angle(2θa). Using the x-y coordinate system given in Figure 2, with starting point O at the vertex of parabola 2, it is simple to establish that the equation for parabola 2

$$y = \frac{x^2}{2 \times b \times (1 + sin\theta_a)} \quad ------ (2)$$

The focal length on the x-axis and the corresponding coordinates of the endpoints of parabola 2 are as follows.

$$OB(Focus) = \frac{b}{2}(1 + sin\,\theta_a) ------ (3)$$

Point C: $x = b\ Cos\ \theta_c$ $\quad y = \frac{b}{2}(1 - sin\,\theta_a)$

Point D: $x = (b + w)cos\theta_a$ $\quad y = \frac{b}{2}(1 - sin\,\theta_a)\left[1 + \frac{1}{sin\,\theta_a}\right]^2$

The concentrator's height-to-aperture ratio can be calculated as below equation 4.

$$\frac{H}{W} = \frac{1}{2}\left[1 + \frac{1}{sin\,\theta_a}\right]\cos\theta_a = \frac{1}{2}(1 + C)\left[1 - \frac{1}{C^2}\right]^{1/2} ------ (4)$$

To get the coordinates for parabola 1 by multiplying the mirror matrix (equation 5.) with the coordinates of parabola 2

$$\begin{bmatrix} \cos 2(90-\theta_a) & \sin 2(90-\theta_a) & 0 \\ \sin 2(90-\theta_a) & -\cos 2(90-\theta_a) & 0 \\ H_v \sin 2(90-\theta_a) - 2H_H \sin^2(90-\theta_a) & 2H_v \cos^2(90-\theta_a) - H_H \sin 2(90-\theta_a) & 1 \end{bmatrix} ------(\mathbf{5})$$

Where, $H_H = \frac{b[1+\sin\theta_a + 2\cos\theta_a]}{4}$, $H_v = \frac{b}{4}(1-\sin\theta_a)$

The surface area of the concentrator (Acon) is determine using equation 6.

$$\frac{A_{con}}{WL} = \sin\theta_a(1+\sin\theta_a) \times \left[\frac{\cos\theta_a}{\sin^2\theta_a} + \ln\left\{\frac{(1+\sin\theta_a)(1+\cos\theta_a)}{\sin\theta_a[\cos\theta_a + (2+2\sin\theta_a)^{1/2}]}\right\} - \frac{\sqrt{2\cos\theta_a}}{(1+\sin\theta_a)^{3/2}}\right] ------(6)$$

Rabl et. al. [16] proved that an average number of reflections m received by all radiation dropping across the acceptance angle before reaching the absorber surface can be calculated by the equation 7.

$$m = \frac{1}{2\sin\theta_a}\left(\frac{A_{con}}{WL}\right) - \frac{(1-\sin\theta_a)(1+2\sin\theta_a)}{2\sin^2\theta_a} ------(7)$$

Thus the effective reflectivity of the concentrator surface is given $\rho_e = \rho^m$

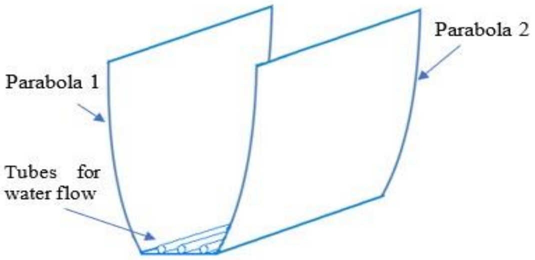

Figure 1: Winstone profile for CPC

Materials used for CPC components include stainless steel sheets, aluminium sheets, thermocole, cardboard, and glass. Low-cost CPC design and fabricated with above mention data in Table 1.

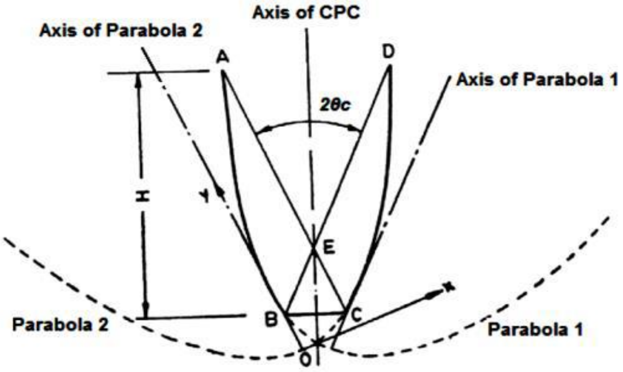

Figure 2. CPC Geometric Design

Sr. No	Geometric Parameters	Value
1	Absorber plate width (**b**)	0.3m
2	Aperture width (**W**)	0.6m
3	CPC length (**L**)	2m
4	No. of tubes(**N**)	03
5	Slope angle ($\boldsymbol{\beta}$)	23°
6	Tube outer diameter ($\mathbf{D_o}$)	11mm
7	Mass flow rate of the Air ($\dot{m}$)	0.0033 kg/min
8	Concentration Ratio	2
9	Acceptance angle(θc)	30°
10	Height of CPC	780mm
11	Focus of CPC	225mm
12	Tube inner diameter($\mathbf{D_i}$)	08mm

Table 1: Geometry Dimension of CPC calculated from equation

2.2 Experimental Procedure

A compound parabolic collector (CPC) water heater consists of an absorber plate wherein the water to be heated flows within a tube situated above or below the absorber plate. Water can be circulated in the CPC by two methods one is Active and the second is passive. In this present work, we have used Passive methods for water circulation and it is more economical.

2.3 Calculations for estimate solar radiations

Experiments are performed on **April 23rd** at Patan **Gujarat**

Latitude (Φ) =23.85° N and Longitude (λ) = 72.13° E of patan,Gujarat,india.

A CPC is mounted on a horizontal east-west axis and oriented with its aperture plane sloping at an angle of 23°.

Angle of Declination: $\delta_s = 23.45 \times sin\left[\frac{360}{365}(284+n)\right] = 12.27^0 - - - - - (8)$

Sunset hour angle: $\omega_s = cos^{-1}[-tan\emptyset \times tan\delta] = 95.44^0 - - - - - (9)$

Ho= the average monthly Extra-terrestrial Radiation at the top of the atmosphere.

$$H_o = \frac{24}{\pi}Gsc \times 3.6\left[\left\{1+0.033\cos\left(\frac{360n}{365}\right)\right\}\left(\cos\phi\cos\delta\sin\omega s + \frac{2\pi\omega s}{360}\sin\phi\sin\delta\right)\right] - (10)$$

H_0=38.37 MJ/m²

Now taking **a = 0.28, b = 0.48** & the range $\left(\frac{\bar{S}}{\bar{S}_{max}}\right) = 0.8$ for the location of Patan.

From the standard tables, we get global as well as diffuse radiation, the daily Global radiation can be calculated as below:

$$H_g = H_o\left\{a+b\left(\frac{\bar{S}}{\overline{Smax}}\right)\right\} - - - - - (11)$$

H_g=25.48 MJ/m²

The daily diffuse radiation can be calculated as below:

$$H_d = H_g\left(1.411 - 1.696\left[\frac{Hg}{Ho}\right]\right) - - - - - (12)$$

H_d= 7.25 MJ/m²

The hourly extra-terrestrial radiation on a horizontal surface for a day can be calculated by obtaining the instantaneous value at the midpoint of the hour.

$I_o = Gsc \times 3600\left[\left\{1+0.033\cos\left(\frac{360n}{365}\right)\right\}(\cos\phi\cos\delta\cos\omega + \sin\phi\sin\delta)\right] - -(13)$

$$\omega = 15 \times (12 - LST) - - - - - (14)$$

$\omega = 15 \times (12 - 12.5) = -3.75^0$ [12.25 represents 12h15m converted in units]

Thus we get, I_o = 4.44 MJ/m²-h = 1233.33W/m²

The hourly Global radiation between 6000h & 7000 h can be calculated as below:

$a = 0.409 + 0.5016 \times \sin(\omega_s - 60^0) = 0.70$ [ω_s=95.44°]

$$b = 0.6609 - 0.4767 \times \sin(\omega_s - 60^0) = 0.38$$

Thus, $I_g = H_g\left\{\frac{I_o}{H_o}(a + b\cos\omega)\right\} - - - - - (15)$

I_g=3.18 MJ/m²-h = 883.33 W/m²

Thus the hourly Diffuse radiation on 1215h is calculated as below:

$$a' = 0.4922 + \{0.27/(H_d/H_g)\} = 1.44$$

$$b' = 2(1-a') \times \frac{sin\omega_s - \omega_s \times cos\omega_s}{\omega_s - 0.5 \times sin2\omega_s} = 1.31$$

Thus,$I_d = H_d\left\{\frac{I_o}{H_o}(a' + b'\cos\omega)\right\} - - - - - (16)$

I_d= 0.84 MJ/m²-h = 233.33 W/m²

The day length of April 23 can be calculated as

$$\bar{S}\max = \frac{2}{15}\cos^{-1}(-\tan\phi\tan\delta) - - - - - (17)$$

$= (^2/_{15}) \times 95.44^0$ $\omega_s = cos^{-1}[tan\varphi \times \underrightarrow{tan\delta]} = 95.44^0$

$$= 12.73\ h$$

3. Calculations for Efficiency

The aperture, which has been covered in an opaque sheet, is expected to slope south at the collector's angle. Due to its wide acceptance angle, a CPC may accept both direct and diffuse radiation. So, it is required to determine direct, diffuse, and global radiation received on the aperture of CPC.

The beam radiation flux on the aperture surface is I_b, whereas its diffuse radiation flux across the acceptance angles I_d. Therefore, the total effective flux across the aperture plane is.

$$I_g = I_b + I_d = 883.3\ W/m^2$$

Mass flow rate of the Air ($\dot{m}$)	0.0033 kg/min
Inlet Temperature (**T_{fi}**)	40°C
Outlet Temperature (**T_{fo}**)	60°C
Ambient Temperature (**T_a**)	44°C
Surface Temperature of Absorber (**T_s**)	64°C
Beam Radiation (Ib)	650 w/m²
Diffuse Radiations (Id)	233.3 w/m²
Total Radiations (Ig)	883.3 w/m²

Table 2: Measured data at CPC

The useful heat gain rate obtained from the below with inlet and out late temperature of the water.

$$q_u = \dot{m}C_p\left[\left(T_{f0} - T_{fi}\right)\right] = 663.21\frac{w}{m^2} - - - - - (18)$$

The instantaneous collecting efficiency is then determined by

$$\eta_i = \frac{q_u}{I_g \times W \times L} \times 100 = 62.59\% - - - - - (19)$$

4. Result and Discussion

The performance analysis of a solar water heater with a compound parabolic collector (CPC) involves assessing various parameters such as efficiency, heat gain, temperature rise, and overall effectiveness in converting solar energy into usable heat for water heating purposes. A CPC is set up on a horizontal east-west axis, with its aperture plane tilting at an angle of 23°. Three tubes are used for the flowing water in the CPC collector. The CPC collector utilized heated air which entered at 40° and this heat was transferred to the water via a tube and finally got the heated water at the outlet tube. Inlet Water and outlet water temperatures were recorded for all trials.

Here's a structured discussion on the results of such an analysis:

- Efficiency is a crucial parameter in evaluating the effectiveness of a solar water heater system. It's typically calculated as the ratio of useful energy output (heat gained by water) to the energy input (solar irradiance). The efficiency of the solar water heater with CPC is 62.59 %.

- Heat gain refers to the amount of thermal energy absorbed by the collector from incident solar radiation. Results typically demonstrate the enhanced heat gain capabilities of CPCs due to their ability to concentrate sunlight onto a smaller receiver area. The performance of the CPC in terms of heat gain is evaluated under varying solar radiation intensities and tilting angle of 23° is 663.21 w/m^2.

- Temperature rise indicates how much the temperature of the water increases as it passes through the solar collector. The temperature rise achieved by the water in the CPC-based solar water heater is 60°. Factors such as flow rate, solar radiation intensity, and collector efficiency influence the temperature rise.

5. Conclusion.

From the current experimental investigation, the following conclusions can be drawn:

- With an efficiency rating of 62.59%, the system showcases its capability to effectively convert solar energy into usable heat for water heating purposes. The substantial heat gain of 663.21 W/m^2 highlights the CPC's efficiency in absorbing thermal energy from incident solar radiation, thereby enhancing its overall performance.
- Additionally, achieving a temperature rise of 60°C underscores the system's effectiveness in elevating the water temperature as it passes through the collector.
- The findings suggest that CPC-based solar water heating systems hold significant potential for sustainable and efficient water heating applications, offering a viable solution towards reducing dependency on conventional energy sources and mitigating environmental impacts.
- Further research and optimization efforts could enhance the performance and applicability of such systems, contributing to the advancement of renewable energy technologies.

6. References

[1] R. Shukla, K. Sumathy, P. Erickson, and J. Gong, “Recent advances in the solar water heating systems: A review,” *Renewable and Sustainable Energy Reviews*, vol. 19, pp. 173–190, Mar. 2013, doi: 10.1016/j.rser.2012.10.048.

[2] D. Nath, D. Ansar, B. Das, and S. Bhuyan, “Experimental analysis of solar water heater with compound parabolic concentrator,” *EAI Endorsed Transactions on Energy Web*, p. 165513, Jul. 2018, doi: 10.4108/eai.13-7-2018.165513.

[3] M. A. Sabiha, R. Saidur, S. Mekhilef, and O. Mahian, “Progress and latest developments of evacuated tube solar collectors,” *Renewable and Sustainable Energy Reviews*, vol. 51, pp. 1038–1054, Nov. 2015, doi: 10.1016/j.rser.2015.07.016.

[4] I. Iparraguirre *et al.*, “Solar Thermal Collectors for Medium Temperature Applications: A Comprehensive Review and Updated Database,” *Energy Procedia*, vol. 91, pp. 64–71, Jun. 2016, doi: 10.1016/j.egypro.2016.06.173.

[5] D. K. Patel, P. K. Brahmbhatt, and H. Panchal, “A review on compound parabolic solar concentrator for sustainable development,” *International Journal of Ambient Energy*, vol. 39, no. 5, pp. 533–546, Jul. 2018, doi: 10.1080/01430750.2017.1318786.

[6] M. J. Muhammad, I. A. Muhammad, N. A. Che Sidik, and M. N. A. W. Muhammad Yazid, “Thermal performance enhancement of flat-plate and evacuated tube solar collectors using nanofluid: A review,” *International Communications in Heat and Mass Transfer*, vol. 76, pp. 6–15, Aug. 2016, doi: 10.1016/j.icheatmasstransfer.2016.05.009.

[7] K. K. Chong, K. G. Chay, and K. H. Chin, “Study of a solar water heater using stationary V-trough collector,” *Renew Energy*, vol. 39, no. 1, pp. 207–215, Mar. 2012, doi: 10.1016/j.renene.2011.08.002.

[8] E. Bellos, D. Korres, C. Tzivanidis, and K. A. Antonopoulos, “Design, simulation and optimization of a compound parabolic collector,” *Sustainable Energy Technologies and Assessments*, vol. 16, pp. 53–63, Aug. 2016, doi: 10.1016/j.seta.2016.04.005.

[9] R. J. Xu, X. H. Zhang, R. X. Wang, S. H. Xu, and H. S. Wang, “Experimental investigation of a solar collector integrated with a pulsating heat pipe and a compound parabolic concentrator,” *Energy Convers Manag*, vol. 148, pp. 68–77, Sep. 2017, doi: 10.1016/j.enconman.2017.04.045.

[10] K. Devanarayanan and K. Kalidasa Murugavel, “Integrated collector storage solar water heater with compound parabolic concentrator – development and progress,” *Renewable and Sustainable Energy Reviews*, vol. 39, pp. 51–64, Nov. 2014, doi: 10.1016/j.rser.2014.07.076.

[11] K. Yoshioka, A. Suzuki, and T. Saitoh, “Performance evaluation of two-dimensional compound elliptic lens concentrators using a yearly distributed insolation model,” *Solar Energy Materials and Solar Cells*, vol. 57, no. 1, pp. 9–19, Feb. 1999, doi: 10.1016/S0927-0248(98)00161-5.

[12] P. Gang, L. Guiqiang, Z. Xi, J. Jie, and S. Yuehong, “Experimental study and exergetic analysis of a CPC-type solar water heater system using higher-temperature circulation in winter,” *Solar Energy*, vol. 86, no. 5, pp. 1280–1286, May 2012, doi: 10.1016/j.solener.2012.01.019.

[13] L. Guiqiang, P. Gang, S. Yuehong, J. Jie, and S. B. Riffat, “Experiment and simulation study on the flux distribution of lens-walled compound parabolic concentrator compared with mirror compound parabolic concentrator,” *Energy*, vol. 58, pp. 398–403, Sep. 2013, doi: 10.1016/j.energy.2013.06.027.

[14] Y. Kim, G. Han, and T. Seo, “An evaluation on thermal performance of CPC solar collector,” *International Communications in Heat and Mass Transfer*, vol. 35, no. 4, pp. 446–457, Apr. 2008, doi: 10.1016/j.icheatmasstransfer.2007.09.007.

[15] Sabah Auda Abdul Ameer* and Haroun A.K Shahad, “Characteristics Review of Optical Concentrators,” *International Journal of Current Engineering and Technology*, vol. 17, no. 1, Feb. 2017.

[16] Rabl, A. (1976). Comparison of Solar Concentrators. Solar Energy , 18, 93-111.