JSER

Journal of Solar Energy Research (JSER)

Journal homepage: www.jser.ut.ac.ir

A Comparative Analysis of Standard and Flat Reflector Integrated Parabolic Trough Solar Collectors for Hot Water Generation

Gunjan Kumar[a*], Amit Galphade[b], Solanki Ankit[a], Sandhya B N[a], Karan Vasava[a]

[a]Department of Mechanical Engineering, UPL University of Sustainable Technology, Ankleshwar, India – 393135
[b]Faculty of Engineering and Technology, Sigma University, Bakrol, Vadodara, India - 390019.

ARTICLE INFO

Article Type:

Research Article

Received:25.07.2024
Accepted:08.03.2025

Keywords:
Parabolic Concentrator;
Solar Collector;
Solar Energy;
Flat Reflector;
Solar Thermal

ABSTRACT

The vital elements of solar thermal technology are solar collectors, which collect solar radiation and produce heat energy. They can be broadly divided into two categories: focused and non-focused. Parabolic trough collectors belong to the type of focused systems that accommodates reflected radiation into a centrally located receiver. Parabolic collectors are commonly employed to fulfill process heat requirements. This paper presents an experimental analysis of a parabolic solar concentrator using both flat and parabolic reflectors. This study investigates the practical performance of a standard and novel flat reflector integrated parabolic trough solar collector while maintaining identical operational conditions. The novel collector's maximum thermal efficiency is recorded as 55%, which is competitive with the standard parabolic trough collector's performance. The average temperature difference of working fluid is 6.85°C, indicating a 1.14°C increase compared to the standard parabolic trough collector that was examined. The findings of this work provides vital information to researchers and scientists working in this field.

1. Introduction

Global warming poses a significant and pressing challenge for developing countries, demanding urgent and effective solutions[1, 2]. One such solution that has gathered considerable attention is using renewable energy sources [1, 3]. An energy source that is considered renewable has nearly zero greenhouse gas and pollution emissions and is sourced from resources that can be regenerated naturally [4–7]. Solar energy is the leading and readily available renewable source on earth for generating heat energy[8, 9]. Solar radiation can be absorbed by the solar collectors, which then convey the energy to the working fluid in the form of heat [10]. There are several kinds of solar concentrators, including parabolic, flat-plate, and linear Fresnel concentrators [10, 11]. A parabolic trough

*Corresponding Author Email: gunjan.kumar@upluniversity.ac.in

Cite this article: Kumar, G. , Galphade, A. , Solanki, A. , BN, S. and Vasava, K. (2025). A Comparative Analysis of Standard and Flat Reflector Integrated Parabolic Trough Solar Collectors for Hot Water Generation. Journal of Solar Energy Research, 10(Emerging Trends in Photothermal Conversion for Solar Energy Harvesting), 1-11. doi: 10.22059/jser.2025.379565.1440

DOI: 10.22059/jser.2025.379565.1440

concentrator (PTC) is a collector that consists of highly reflective reflectors. It exhibits linearity in one dimension and takes on a parabolic shape along the other two dimensions. [12–15]. The receiver is positioned along the focus line of PTC to receive the reflected radiations. [16, 17]. The PTC schematic diagram is displayed in Figure 1.

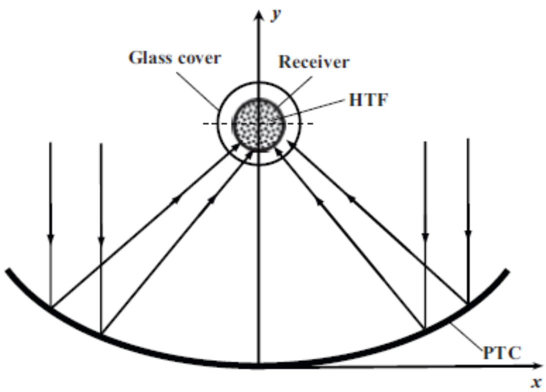


Figure 1. Diagram of PTC [18]

Parabolic solar technology can be divided into two main categories, each having its own uses and implications [19]. Large-scale PTC falls under the first type and is usually employed for energy generation. Temperatures as high as 400°C can be attained with this technology [20, 21]. Its importance in electricity production cannot be overemphasized because it supports in lowering the utilization of fossil fuels and the release of greenhouse gas emissions. Researchers and inventors around the world, however, are particularly interested in the second kind of PTC. This area encompasses applications such as water distillation, food processing, air conditioning and refrigeration, process heating, and more [20]. Scientists and engineers have been working hard to investigate the many opportunities in this area for a variety of sustainable energy applications. The core components of a PTC include the reflector, receiver, supporting structure, tracking system, and energy storage system [21]. Researchers have optimized these components to enhance collector efficiency and application adaptability. The global effort to combat climate change and shift towards cleaner, more sustainable energy sources is aided by the advancement of heat transfer fluids, mass flow rate control, intercept factor optimization, reflectivity enhancements, and a variety of applications of this technology in different sectors. [22, 23]. The evolution and ongoing research in this field are crucial steps towards mitigating the adverse effects of global warming and building a more sustainable future. The usual characteristics of existing PTCs are illustrated in Table 1.

Table 1.Characteristics of PTC

Parameters	Remarks	Sources
Collector efficiency	Highest in line focus technology	[24]
Operating cost	Cost is high due to tracking of reflector-receiver assembly	[25,26]
Absorber	Absorber is integrated with reflector and participate in tracking	[27]
HTF choice	Rotating absorber causes the leakage of HTF and makes the choice l limited	[28]

PTC has more than 130 years of history. In the 1880s, John Ericsson invented the PTC, which was used to run a steam engine [29]. This concept was applied for irrigation in the Nile river basin by Shumand and Boys in 1912 [30]. Researchers were attracted to the PTC system because of its versatility, but the production of electricity remained the most important usage because of the system's capacity to generate temperatures as high as 400°C [31]. PTC offers several benefits, including a large power capacity, modularity, high efficiency, adaptability, extended lifespan, and resistance to moisture. There are also drawbacks, such as the need for a large amount of land, the tracking system's high maintenance costs, the receiver's gradual deformation, and the use of moving elements [32]. It has been discovered that combining PTC systems as backup support with traditional gas-based power plants can boost plant output and lower the cost of producing electricity [33]. Global CSP-based power plant capacity was close to 1 GW as of 2010; this amount is expected to rise by 7% and 25%, respectively, by 2030 and 2050 [34]. In 2012, Ready et al. [35] carried out an analysis of the generation of electric power using water and oil as heat transfer fluids (HTFs). Nanofluids are becoming more popular for solar applications due to their superior thermophysical characteristics[36]. Techno-economic feasibility studies are conducted for 58 different solar thermal power plant locations in India [35].

Researchers have shown interest in various aspects of PTCs to unlock the full potential of this technology for sustainable energy solutions [37–39]. Eleazar et al. [40] have exhibited a noteworthy design innovation on PTC constructions. This innovation lowered production costs and speeded up installation by combining innovative manufacturing techniques with well-chosen materials. It also improved structural integrity. This particular PTC configuration finds application in solar thermal systems that produce process heat. Additionally, this PTC design has a novel tracking system that makes use of a traction wheel mechanism. During testing, the PTC reached a peak temperature of 80°C and a flow rate of 0.5 litres per second, but with a slightly lower efficiency of 60%. [40]. These developments underscore the ongoing efforts to refine PTC technology, making it more efficient, accessible, and adaptable in pursuing sustainable energy solutions.

The reflector is the key component of PTC technology, having a significant impact on collector performance. In fact, the reflector's condition has a major impact on the PTC's optical efficiency. Reflectors come in many different shapes and sizes, and common materials used are acrylic mirrors, stainless steel sheets, aluminum foil, and aluminium sheets. Testing was done on a prototype of PTC composed of fiberglass-reinforced plastic and coated in aluminium foil, which had a reflectivity of 0.86 [41]. A mild steel receiver covered in black proxy material was also investigated, both with and without a glass cover. The notable findings from these investigations revealed an efficiency of 51% and 39% when both with and without the glass cover were considered. [41]. Sagade et al. [42] reported on test results employing a different prototype PTC in a separate study. In this case, a 10-micron-thick aluminium foil was applied to the PTC's surface to serve as a reflector. They carried out thorough evaluations of many receivers and succeeded in raising the temperature to 81.70°C by applying a selective coating of silver chrome to the copper receiver [42]. These results demonstrate the ongoing progress in this sector by highlighting the importance of reflector selection and its direct impact on PTCs' performance and heat output.

Parabolic collector technology has grown primarily because of receiver design innovations. A rhombus-shaped receiver for PTCs was introduced by Donga and Kumar [43], who showed a noteworthy 31.5% gain in performance over traditional circular receivers with a comparable concentration ratio at a 90° rim angle. The rhombus-shaped receiver is efficient at rim angles between 75° and 90°, according to numerical simulations, and it maximizes space utilization by having a 13.8% smaller footprint than a circular receiver. Peng et al. [44] made a significant contribution to this innovation by creating a PTC single-pass absorber made entirely of glass. In order to optimize the bellows that hold the absorber tube, they performed numerical simulations. Their efforts resulted in a temperature range of 540 K to 330 K, with a thermal efficiency range of 62% to 72% [45]. Jafar et al. [45] examined the impact of conical inserts inside the receiver tube. The conical strip inserts improved the PTCs' thermal characteristics by creating swirls, which raised the rates of heat transfer and friction. Their findings demonstrated how important it is to consider insert configuration and receiver shape when designing PTC systems in order to maximize system performance and thermal efficiency. In an attempt to innovate, Upadhyay et al. [46] have presented a unique PTC design that makes it easier to assemble and transport while enabling the simple replacement of important parts such as the working fluid, reflector facet, and receiver pipe. A notable feature of this design was its elimination of flexible joints, addressing the issue of leakage often associated with traditional receiver configurations. A prototype PTC was rigorously examined during their investigation to assess its practical, optical, and thermal efficiencies. The study was carried out on three different reflector materials (acrylic mirror, aluminium sticker foil, and chrome sticker) and three distinct receiver materials (copper, aluminium, and G.I.), each tested with and without black graphite paint coating. Notably, no glass cover was employed on any receivers, reflecting a unique approach to PTC design and its potential to meet specific energy needs [46].

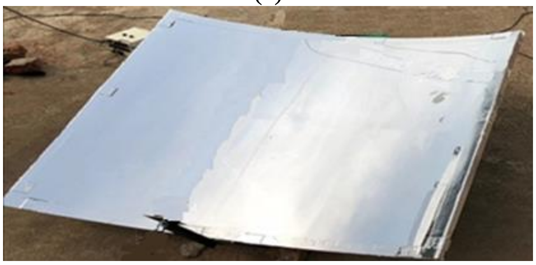
The literature study underlines how PTCs are suitable for multiple domains due to their diversity in terms of size, design, and temperature range. The aim of this study is to examine the PTC's experimental performance when integrated with flat reflectors. The current work's novelty lies in its incorporation of flat reflectors with a conventional parabolic reflector. The development of a flat reflector combined parabolic concentrator makes the concept unique. The outcome could encourage the relevant industries to meet their industrial demands. The paper is arranged such that Section 2 provides an illustration of the experimental setup and process of the experimentation. Section 3 presents the results and discussion, and the remainder of 4 concludes the work.

2. Materials and Methods

2.1. Experimental Set up

A testing setup was installed at an engineering college located in Ankleshwar (21.6°N, 72.7°E), India. The setup consists of a single parabolic trough where a single fixed receiver is placed along the focal line of a parabola. The parabolic trough is surrounded by four flat reflectors that are carefully positioned to focus sunlight onto the receiver. The parabolic trough is kept stationary to keep the receiver steady. Additionally, the fixed receiver removes the restriction on the variety of heat transfer fluids (HTFs). Components of the setup are depicted in Figure 2. Flat reflectors are given a tracking facility to maximize the radiation on the receiver. Every flat reflector includes a solar-powered tracking device that operates independently under a controller's direction. The schematic representation of the setup, including the instrument locations, is illustrated in Figure 3.

(a)



(b)

(c)

Figure 2. (a) Flat reflector (b) Parabolic trough (c) Absorber

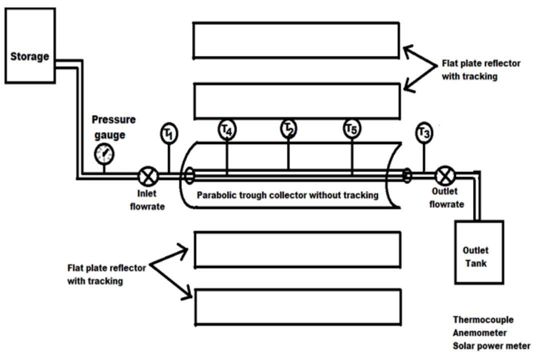


Figure 3.Experimental setup schematic with instrument location

The receiver is cylindrical and enclosed under a protective glass cover to maximize solar energy absorption. Figure 4 shows an actual photograph of the experimental setup. Table 2 presents the geometrical specifications of the components used in the setup.

Figure 4. Photograph of the developed prototype

Table 2. Specifications of experimental setup

Name of components	Nos.	Dimensions	Materials
Parabolic trough	1	Length, L= 1.23 m, Width, W = 1m, Aperture area = 0.8m^2	Acrylic Sheet
Flat reflector	4	Length, L=2m, Width, W=0.5m	Acrylic Sheet
Receiver	1	Diameter, D= 1.25cm, Length, L= 1.23m	Galvanized Iron with glass envelope

2.2. Experimentation Process

An appropriate testing protocol has been followed to conduct the experimentation [47, 48]. Figure 5 depicts the experimental process flow chart based on the chosen protocol. The temperature of the water, solar radiation, wind speed, and surrounding air were measured every ten minutes. Each experiment was conducted twice to ensure the results could be replicated across 5 hours (10:00 AM to 4:00 PM). The collector was tested in the dynamic climatic conditions of Ankleshwar, Gujarat, India, during the month of April 2023.

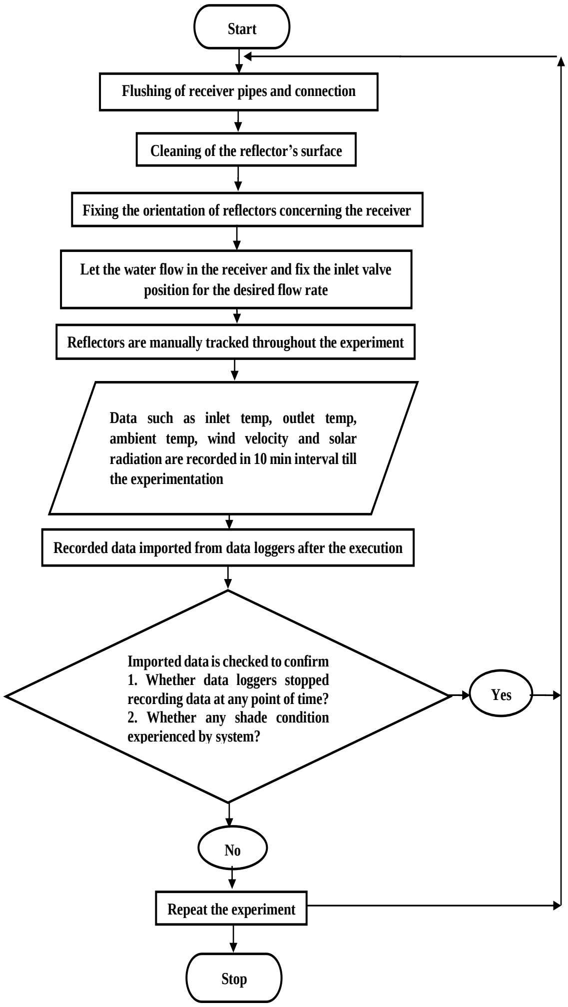


Figure 5. Flow chart of the testing process

The system's performance is tested under clear-sky conditions and over its operational temperature range. Quasi-steady-state conditions are used for the measurements. For the thermal evaluation, tap water is the heat transfer fluid (HTF), with a low mass flow rate maintained at 0.033 kg/s [49]. The flow rate is measured using a simple but reliable technique that involves precisely timed stopwatch readings and marked beakers. A regulating valve is positioned to help regulate the flow rate properly and maintain a constant flow rate during the testing procedure. Precised and calibrated instruments were used to take periodic measurements of variables, including water inlet temperature (T_i), exit temperature (T_o), wind velocity (V), and solar insolation (I). Table 3 lists the instruments used to measure variables during the experiment.
The following assumptions are made during the experiment[48].

- System is in quasi steady-state during observation.
- Specific heat of water remains constant during operation.
- All measuring instruments show actual parameters.
- Total solar energy reflected is fully utilized for water heating.
- The mass flow rate of water during a set of experiment remains constant.

Table 3.List of Instruments for the measurement of parameters

Instruments	Parameters
Pyrheliometer Range:2000W/m^2 Uncertainty = 0.58%	Solar radiation
Temperature Sensor 100 Ω PLT 4 wire RTD / J Type Thermocouple Accuracy: ± 1°C, Range: 0-1200 °C	Temperature
Anemometer Accuracy within ± 5%, Air velocity Range 0.4 – 30 m/s Uncertainty = 0.17	Air velocity

The performance of the collector is assessed based on temperature difference, heat generation, and thermal efficiency [47, 48]. The temperature difference, ΔT has been computed by subtracting the exit temperature of hot water from the inlet temperature of water.

$$Q_a = m_f\, C_p\, \Delta T \qquad (1)\ [50]$$

$$\frac{1}{U_o} = \frac{1}{U_i} + \frac{D_o}{h_i D_i} + \frac{D_o ln\frac{D_o}{D_i}}{2K} \qquad (2)\ [49]$$

$$\frac{1}{U_i} = \frac{1}{h_w} + \frac{1}{h_r} \qquad (3)\ [49]$$

$$Q_r = (FR)\ A_a[I_b - \left(\frac{A_p}{A_a}\right) U_i(T_p - T_a)] \qquad (4)\ [49]$$

$$\eta_{th} = \frac{Q_a}{I_b\ A_a} \qquad (5)\ [51]$$

Equation (1) is used to evaluate the useful heat energy gained by water Q_a. Equation (2) describes the overall heat transfer coefficients from the liquid to the surrounding in association with conduction, convection, and radiation. The overall heat loss is linked to the overall heat transfer coefficient. Overall heat loss is calculated using the available solar energy at the receiver and the exit temperature of water or steam. U_o and U_i stand for overall heat transfer and inside heat transfer coefficients, respectively. The outside and inside diameters of the receiver are designated as D_o and D_i, respectively. The thermal conductivity and convective heat transfer coefficient are denoted by K and h_i, respectively. The effects of convection and radiation are considered in equation (3). The coefficients of wind heat transfer and surface heat transfer are h_w and h_r, respectively. Equation (4) represents the heat received by receiver, Q_r using the energy balance equation across the absorber pipe, accounting for all forms of losses and governing parameters. FR stands for heat removal factor, whereas A_p and A_a represent receiver and effective reflector area, respectively. I_b represents the beam radiation, while T_p and T_a denote the receiver and ambient temperature, respectively. Collector efficiency can be determined using equation (5) [51].

3. Results and Discussion

The experimental outcomes and thermal analysis of the collector are covered in this section. The setup was installed and tested at the testing site's open location. During the entire experimentation period, an average beam radiation of 536.42 W/m^2 was recorded. The observed average wind speed and ambient temperature are 2.3 m/s and 33.95 °C, respectively. The measurement and assessment of crucial performance parameters are presented in Table 4.

Table 4.Experimental outcomes of a novel collector in April 2023

Time	T_i	T_o	ΔT	V	I	Q_r	Q_a
Hrs.	°C	°C	°C	m/s	W/m^2	Watt	Watt
10:00	25.7	29.1	3.3	2.2	681	1942	473
11:00	26.2	33.2	7.1	2.2	902	2571	974
12:00	27.1	37.7	10.5	1.7	1012	2893	1476
13:00	29.1	41.3	12.3	1.4	1104	3141	1726
14:00	29.1	37.3	8.1	2.6	963	2745	1113
15:00	28.3	32.6	4.4	2.9	795	2279	627
16:00	28.2	30.2	2.1	2.5	487	1396	278

In parallel, experimental data were also collected for a conventional PTC during these same test conditions. The thermal efficiency (η_{th}) and temperature difference (ΔT) were calculated and are presented in Table 5 for varying time durations. Notably, the novel collector consistently exhibited higher temperature differences due to flat reflector tracking. However, it was found that the novel collector's efficiency was somewhat lower, which was caused by the smaller temperature differential ratio to the aperture area. These results provide important new information about the benefits and drawbacks of changing the collector design in a search for more sustainable and effective solar energy systems. Figure 6 shows the variation in solar radiation during the experiment. The sun's position and associated solar angles determine how radiation varies. It has been shown that radiation rises, peaks, and then starts to fall during the execution period. It is noteworthy that the solar radiation peaks at 13:00 hours, reaching a remarkable 1100 W/m^2, and then begins to decrease.

Table 5. Performance comparison of collectors, April, 2023

Time	Conventional PTC		Novel PTC (Flat reflector integrated)	
Hrs.	ΔT(°C)	η_{th} (%)	ΔT(°C)	η_{th} (%)
10:00	2.5	25.2	3.41	24.35
11:00	5.8	38.2	7.0	37.80
12:00	8.7	52.3	10.5	50.98
13:00	11.0	56.1	12.4	54.93
14:00	6.5	41.7	8.1	40.57
15:00	3.7	28.3	4.5	27.47
16:00	1.2	20.8	2.1	19.92

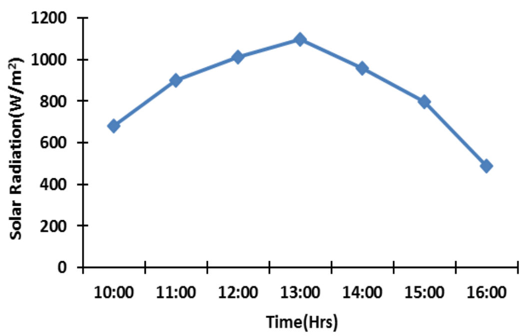


Figure 6. Variation of solar radiation, April 2023

Hot water has been produced at the receiver's outlet. During the testing, the water temperatures at the collectors' input and exit are continuously monitored. The monthly average temperature difference of working fluid are shown in Figure 7. It is noteworthy that, although the mean temperature difference is claimed to be 6.85°C, the largest differential between the two collectors was just 1.8°C. Maximum temperatures are typically recorded between 12:00 p.m. and 1:00 p.m. because of the sun's overhead position. The substantial heat flux available at the receiver that arises from tracking flat reflectors leads to higher exit temperature values for novel collectors.

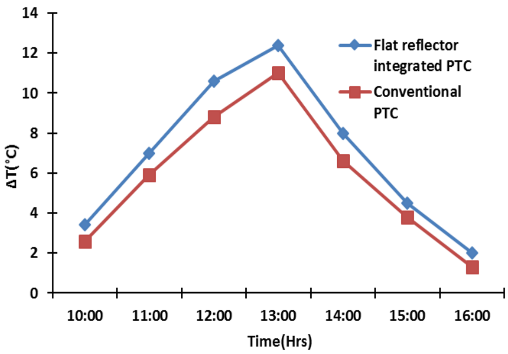


Figure 7. Variation of temperature difference, April 2023

Using equation (5), the thermal efficiency of each collector was determined. Figure 8 displays the thermal efficiency of both collectors under the same environmental conditions. It is clear that both collectors' performance patterns are almost exactly the same, with very slight variations seen over time. The integrated area of the reflecting surface results in a slightly decreased thermal efficiency for the flat reflector integrated collector. The highest recorded thermal efficiency was 54.94% at 13:00 hours, while the lowest recorded thermal efficiency was 19.93% at 16:00 hours.

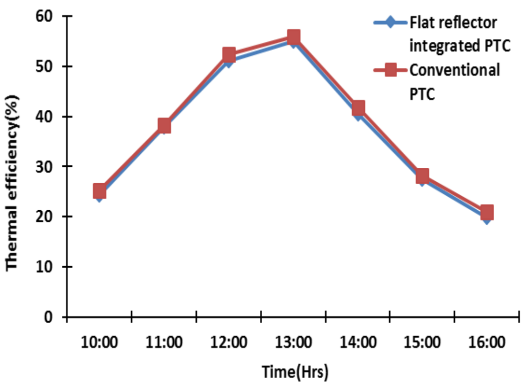


Figure 8. Variation of thermal efficiency, April 2023

These results highlight the superior performance and potential thermal efficiency of the novel collector. In an attempt to conduct a comparison analysis, Figure 9 compares and displays the performance of the collectors under similar climatic condition. Table 6 illustrates the salient features of a developed collector.

Table 6. Features of Novel PTC

Parameters	Remarks
Temperature difference	High due to continuous tracking of flat reflectors
Thermal efficiency	Almost same due to higher temperature difference
Receiver position	Fixed as trough is stationary
HTF'S Choice	Not limited to water as receiver position is stationary
Tracking cost	Less due to tracking of only flat reflectors

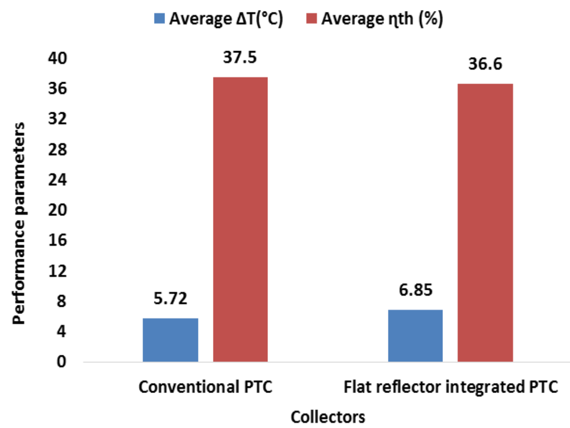


Figure 9. Performance comparison of conventional PTC and flat reflector integrated PTC

4. Conclusions

- Parabolic concentrators are noted for their remarkable optical behaviour, making them a popular choice for heating applications. However, PTC is difficult to operate and deploy due to factors such as receiver mobility, tracking costs, the selection of appropriate heat transfer fluids, manufacturing complexity, and so on.
- In this work, the objective is to leverage on the combined advantages of parabolic trough and flat linear reflectors, successfully reducing the drawbacks. Tracking devices are carefully implemented for the flat reflectors, considerably decreasing tracking-related expenses.
- A combination of parabolic troughs and flat linear reflectors creates novel configurations. While flat reflectors expand the aperture, the parabolic trough adds optical performance characteristics. The parabolic trough is kept in a constant position to ensure that the receiver remains stationary.
- Experimental testing is done on the prototype. Measured output parameters under the same circumstances are compared to the conventional

PTC. The graphs are plotted to notice and contrast the patterns of parameter variations throughout the day. Water has an average temperature difference of 6.85 °C, which is 1.14 °C higher than conventional PTC. It has been noticed that the novel prototype has a thermal efficiency of up to 54.94%, which is little lower than the standard PTC. Novel collector presents a strong possibility for solar energy systems that are both efficient and sustainable.

Future Work

It is expected that altering the receiver surface geometry will improve the performance of the tested novel collector. Furthermore, the application of solar selective coatings can greatly improve performance. The improvement of heat transfer can be significantly impacted by the use of nano fluids. It is required to accompany the collector with a system to store the sensible and latent heat.

Nomenclature

A_a	Effective reflector area (m^2)
A_p	Receiver area (m^2)
C_p	Specific heat capacity (kJ/kg K)
D	Diameter (m)
D_i	Inside diameter of the receiver (m)
D_o	Outside diameter of the receiver (m)
FR	Heat removal factor
h_i	Convective heat transfer coefficient (W/m^2K)
h_r	Coefficients of surface heat transfer (W/m^2K)
h_w	Coefficients of wind heat transfer (W/m^2K)
I	Solar insolation (W/m^2)
I_b	Beam radiation (W/m^2)
K	Thermal conductivity (W/mK)
L	Length (m)
m_f	Mass flow rate (kg/s)
Q_a	Useful heat gain by water (W)
Q_r	Heat available at receiver (W)
T_a	Ambient temperature (° C)
T_i	Water inlet temperature (° C)
T_o	Water exit temperature (° C)
T_p	Receiver temperature (° C)
U_i	Inside heat transfer coefficients (W/m^2K)
U_o	Overall heat transfer coefficients (W/m^2K)
V	Wind velocity (m/s)
W	Width (m)
η_{th}	Thermal efficiency (%)
ΔT	Temperature difference (°C)

References

1. Ram, S., Ganesan, H., Saini, V., & Kumar, A. (2023). Performance assessment of a parabolic trough solar collector using nanofluid and water based on direct absorption. *Renewable Energy*, 214, 11-12. https://doi.org/10.1016/j.renene.2023.06.016
2. Chinnappan, T., Raguraman, C.M., Dhairiyasamy, R., & Rajendran, S. (2024). Comparative Analysis of Polycarbonate and Glass Cover Configurations for Enhanced Thermal Efficiency in Flat Plate Solar Collectors for Water Heating. *Journal of Solar Energy Research*, 9(1), 1794-1810. https://doi.org/10.22059/jser.2024.374268.1394
3. Kumar, G., & Gupta, H. (2022). Optical design of integrated line and point focus solar collector for process heat generation. *Int. J. Environmental Technology and Management*, 25, 218-232. https://doi.org/10.1504/IJETM.2022.122631
4. Sarwara, J., Georgakis, G., Kouloulias, K., & Kakosimos, K.E. (2015). Experimental and numerical investigation of the aperture size effect on the efficient solar energy harvesting for solar thermochemical applications. *Energy Convers Manag*, 92, 331–41. https://doi.org/10.1016/j.enconman.2014.12.065
5. Francesco, G., & Peter, Z. (2013). Exploring the uncertainty around potential shale gas development – a global energy system analysis based on TIAM (TIMES Integrated Assessment Model). *Energy*, 57, 443–57.https://doi.org/10.1016/j.energy.2013.06.006
6. Wang, F.Q., Cheng, Z.M., Tan, J.Y., Zhang, J.Q., Leng, Y., & Liu, L.H. (2017). Energy storage efficiency analyses of CO_2 reforming of methane in metal foam solar thermochemical reactor. *Appl Therm Eng*, 111, 1091–100. https://doi.org/10.1016/j.applthermaleng.2016.10.025
7. Neven, D., Zvonimir, G., Vyatcheslav, K., Jiří, J. K., Brian, M., & Yan, J.Y. (2013). Sustainable development of energy, water and environment systems. *Appl Energy*, 101, 3–5. https://doi.org/10.1016/j.apenergy.2012.08.002

8. Mostafa, A.A., Yasser, E., Mohamed, B., Thokozani, M., Monica, T., Al-Qabandi, O.A., & Sameh, S.K. (2024). Performance enhancement of flat-plate and parabolic trough solar collector using nanofluid for water heating application. *Results in Engineering*, 21, 101673. https://doi.org/10.1016/j.rineng.2023.101673
9. Josué, F.R.P., Andrés, V.J., Manuel, P.G., José, M. C., & Rodrigo, E. (2024). Techno-economic analysis of hybrid solar thermal systems with flat plate and parabolic trough collectors in industrial applications. *Alexandria Engineering Journal*, 86, 98-119. https://doi.org/10.1016/j.aej.2023.11.056
10. Jebasingh, V.K., & Joselin, H.G.M. (2016). A review of solar parabolic trough collector. *Renewable and Sustainable Energy Reviews*, 54, 1085–1091. https://doi.org/10.1016/j.rser.2015.10.043
11. Ghaedi, A., Sedaghati, R., & Mahmoudian, M. (2023). Reliability Evaluation of Solar Power Plants Equipped with parabolic Trough Reflectors. *Journal of Solar Energy Research*, 8(3), 1635-1650. https://doi.org/10.22059/jser.2023.359179.1305
12. Eck, M., & Hennecke, K. (2007). Heat transfer fluids for future parabolic trough solar thermal power plants. In: Goswami DY, Zhao Y, editors. . Proceedings of ISES world congress, Vol. I–Vol. V. Berlin, Heidelberg: Springer. https://doi.org/10.1007/978-3-540-75997-3_369
13. Cheng, Z.D., He, Y.L., Xiao, J., Tao, Y.B., & Xu, R.J. (2010). Three–dimensional numerical study of heat transfer characteristics in the receiver tube of parabolic trough solar collector. *Int Commun Heat Mass*, 37(7), 782–7. https://doi.org/10.1016/j.icheatmasstransfer.2010.05.002
14. Qiu, Y., Li, M.J., He, Y.L., & Tao, W.Q. (2017). Thermal performance analysis of a parabolic trough solar collector using supercritical CO_2 as heat transfer fluid under non–uniform solar flux. *Applied Thermal Engineering*, 115, 1255-1265. https://doi.org/10.1016/j.applthermaleng.2016.09.044
15. Hachicha, A.A., Rodríguez, I., Capdevila, R., & Oliva, A. (2013). Heat transfer analysis and numerical simulation of a parabolic trough solar collector. *Appl Energy*, 111(11), 581–92. https://doi.org/10.1016/j.apenergy.2013.04.067
16. Khanna, S., Kedare, S.B., & Singh, S. (2014). Deflection and stresses in absorber tube of solar parabolic trough due to circumferential and axial flux variations on absorber tube supported at multiple points. *Sol Energy*, 99(1), 134–51. https://doi.org/10.1016/j.solener.2013.11.005
17. Khanna, S., Singh, S., & Kedare, S.B. (2015). Explicit expressions for temperature distribution and deflection in absorber tube of solar parabolic trough concentrator. *Sol Energy*, 114, 289–302. https://doi.org/10.1016/j.solener.2015.01.044
18. Wang, F., Cheng, Z., Tan, J., Yuan, Y. Shuai, Y., & Liu, L., (2017). Progress in concentrated solar power technology with parabolic trough collector system: A comprehensive review. *Renewable and Sustainable Energy Reviews*, 79, 1314–1328. https://doi.org/ 10.1016/j.rser.2017.05.174
19. Kumar, G., & Gupta, H. (2021). A Study of Linear Fresnel Solar Collector Reflector Field for Performance Improvement. In: Recent Advances in Mechanical Infrastructure. *Lecture Notes in Intelligent Transportation and Infrastructure. Springer*, Singapore. https://doi.org/10.1007/978-981-33-4176-0_31
20. Goswami, Y.D. (1998). Solar thermal power technology: Present status and ideas for the future. Energy Sources. 20 (2), 137–45. https://doi.org/ 10.1080/00908319808970052
21. Kalogirou, S.A. (2004). Solar thermal collectors and applications. Progress in energy and combustion science. https://doi.org/10.1016/j.pecs.2004.02.001
22. Vaghasia, J.G., Ratnadhariya, J.K., Panchal, H., & Kumar, K. (2019). Experimental performance investigations on various orientations of evacuated double absorber tube for solar parabolic trough concentrator. *International Journal of Ambient Energy*, 1–17. https://doi.org/10.1080/01430750.2019.1653980
23. Bhavsar, N., Prajapati, D., Patel. S., Vaghela, S., & Upadhyay, B. (2019). New

technique for water desalination using novel solar still and parabolic trough collector. *Journal of Emerging Technologies and Innovative Research*, 6, 342–46. Available at: http://www.jetir.org/papers/JETIRCQ06064.pdf
24. Upadhyay, B.H., Patel, A.J., & Ramana, P.V. (2017). Parabolic trough collector, a novel design for domestic water heating application. International *Journal for Research in Applied Science and Engineering Technology*, 5, 497–503. https://doi.org/10.22214/ijraset.2017.10073
25. [Abbas, M., Boumeddane, B., Said, N., & Chikouche, A. (2011). Dish Stirling technology: a 100 MW solar power plant using hydrogen for Algeria. *Int J Hydrogen Energy*, 36(7), 4305–14. https://doi.org/10.1016/j.ijhydene.2010.12.114
26. Baharoon, D.A., Rahman, H.A., Wan, W.Z., & Fadhl, S.O. (2015). Historical development of concentrating solar power technologies to generate clean electricity efficiently – A review. *Renewable and Sustainable Energy Reviews*, 41, 996-1027 https://doi.org/10.1016/j.rser.2014.09.008
27. Mills, R.D., & Morrison, L.G. (1999). Compact linear Fresnel reflector solar thermal power plants. *Solar Energy*, 68, 263–283. https://doi.org/10.1016/S0038-092X (99)00068-7
28. Guangdong, Z., Tim, W., Michael, W.J., & Chuck, K. (2014). History, current state, and future of linear Fresnel concentrating solar collectors. *Solar Energy*, 103, 639–652. https://doi.org/10.1016/j.solener.2013.05.021
29. Jaber, A., Mariah, N., Zainal, M., Kadir, A., & Aziz, A. (2018). Review of Solar Parabolic-Trough Collector Geometrical and Thermal Analyses, Performance, and Applications. *Renewable & Sustainable Energy Reviews,* 91, 822–831. https://doi.org/ 10.1016/j.rser.2018.04.085
30. Taylor, P., Haddock, C., & Mckee, J.S.C. (2007). Solar Energy Collection, Concentration, and Thermal Conversion — A Review. *Energy sources*, 13, 461–482. https://doi.org/10.1063/1.2718755
31. Jebasingh, V.K., & Herbert, G.M.J. (2016). A Review of Solar Parabolic Trough Collector. *Renewable and Sustainable Energy Reviews*, 54, 1085–1091. https://doi.org/ 10.1016/j.rser.2015.10.043
32. Kaygusuz, K. (2009). Environmental Impacts of the Solar Energy Systems. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effect*, 31 (15), 1376–1386. https://doi.org/ 10.1080/15567030802089664
33. Yogi, Goswami, D. (1998). Solar Thermal Power Technology: Present Status and Ideas for the Future. *Energy Sources*, 20 (2), 137–145. https://doi.org/10.1080/00908319808970052
34. Ummadisingu, A., & Soni, M.S. (2011). Concentrating Solar Power - Technology, Potential and Policy in India. *Renewable and Sustainable Energy Reviews*, 15 (9), 5169–5175. https://doi.org/10.1016/j.rser.2011.07.040
35. Reddy, K.S., & Kumar, K.R. (2012). Solar Collector Field Design and Viability Analysis of Stand-Alone Parabolic Trough Power Plants for Indian Conditions. *Energy for Sustainable Development*, 16 (4), 456–470. https://doi.org/10.1016/j.esd.2012.09.003
36. Olusola, B., Dongsheng, C., Humphrey, A., Michael, A., Mustafa, D., Ferdinard, D., & Huang, Q. (2022). A brief review and comparative evaluation of nanofluid application in solar parabolic trough and flat plate collectors. *Energy Reports*, 8, 156-166. doi.org/10.1016/j.egyr.2022.08.078.
37. Bhargav, H., Ramani, B., & Reddy, V. S. (2018). Experimental study on adsorption capacity of an activated carbon-based adsorption water chiller. *International Journal of Ambient Energy*, 40(6), 657–660.https://doi.org/10.1080/01430750.2017.1421580
38. Thakkar, H., Sankhala, A., Ramana, P. V., & Panchal, H. (2018). A detailed review on solar desalination techniques. *International Journal of Ambient Energy*, 41(9), 1066–1087. https://doi.org/10.1080/01430750.2018.1490351
39. Panchal, H., & Bhargav, H. (2019). Mini-review of different co-generation systems: solar thermal perspective. *International Journal of Ambient Energy*, 43(1), 1–3. https://doi.org/10.1080/01430750.2019.1568912
40. Eleazar, I., Montes, P., Mejia, A., & Mercado, O. (2014). Design and construction of a parabolic trough solar collector for process heat production.

Energy Procedia, 57, 2149–58. https://doi.org/10.1016/j.egypro.2014.10.181

41. Sagade, A., & Shinde, N. (2012). Performance evaluation of parabolic dish type solar collector for industrial heating application. *International Journal of Energy Technology and Policy*, 8 (1), 80. https://doi.org/10.1504/IJETP.2012.046015
42. Sagade, A.A., Shinde, N.N., & Patil, P.S. (2014). Effect of receiver temperature on performance evaluation of silver coated selective surface compound parabolic reflector with top glass cover. *Energy Procedia*, 48, 212–22. https://doi.org/10.1016/j.egypro.2014.02.026
43. Donga, R.K., & Kumar, S. (2018). Parabolic trough collector with rhombus tube absorber for higher concentration ratio. *Energy sources, Part A recover. Util. Environmental Effects*, 40, 2620–31. https://doi.org/10.1080/15567036.2018.1505981
44. Peng, Y., Ren, T., Xia, B., Wang, Y., & Zhu, Y. (2019). Numerical investigation of a novel single-pass all-glass receiver for parabolic trough collector. *Energy sources, Part A recover. Util. Environmental Effects*, 1–15. https://doi.org/10.1080/15567036.2019.1668084
45. Jafar, K.S., Arulprakasajothi, M., Beemkumar, N., & Elangovan, K. (2019). Effect of conical strip inserts in a parabolic trough solar collector under turbulent flow. *Energy sources, Part A recover. Util. Environmental Effects*, 1–13. https://doi.org/10.1080/15567036.2019.1650850
46. Upadhyay, B. H., Patel, A. J., & Ramana, P. V. (2019). A detailed review on solar parabolic trough collector. International Journal of Ambient Energy, 43(1), 176–196. https://doi.org/10.1080/01430750.2019.1636869
47. IS 16648 (Part 5) (2017). Concentrated Solar Thermal — Specification, Test Methods.
48. Upadhyay, B. H., Patel, A. J., & Ramana, P. V. (2020). Comparative study of parabolic trough collector for low-temperature water heating. *Energy Sources, Part A: Recovery, Utilization, and Environmental Effects*, 46(1), 9821–9837. https://doi.org/10.1080/15567036.2020.1779874
49. Kumar, G., & Gupta, H. (2021) Experimental investigation of a line focus solar collector using flat and parabolic reflector. *In: Lecture Notes in Mechanical Engineering*, Springer, Singapore. https://doi.org/10.1007/978-981-16-4222-7_84.
50. Didi, F., Saleh, E.A.M., Kumar, A., Alawadi, A., Alsaalamy, A., Alawsi, T., Alayi, R., Hosseinzadeh, H., & Morovati, R. (2024) Modeling and optimizing the thermodynamics of a flat plate solar collector in transient mode for economic purposes. AIP Advances 14 (1), 015302, https://doi.org/10.1063/5.0185818.
51. Incropera FP, DeWitt DP (Eds.). (1999) Fundamentals of Heat Transfer. Wiley.