Applied Chemical Engineering (2025) Volume 8 Issue 3 ISSN: 2578-2010 (O)
doi: 10.59429/ace.v8i3.5734

ORIGINAL RESEARCH ARTICLE

Experimental investigation of a hybrid compound parabolic collector integrated with flow through-type evacuated tube collector under hot and humid conditions in India

Mohammad Ishrar Jiva[1*], Mohsin J. Dadi[2*], Vijayalaxmi V B[3], Amit Manubhai Patel[4], Jeetendra Dhamone[5], Choon Kit Chan[6]

[1] *Faculty of Engineering and Technology, Parul University, Waghodia, Vadodara, Gujarat, 391760, India.*

[2] *Department of Mechanical Engineering, Parul Institute of Engineering and Technology, Faculty of Engineering and Technology, Parul University, Waghodia, Vadodara, Gujarat,391760, India.*

[3] *Project Engineer, Karnataka State Pollution Control Board, Dharwad, Karnataka, 580004, India*

[4] *Lecturer in Mechanical engineering, Government polytechnic Ahmedabad, Gujarat, India.*

[5] *Department of Mechanical Engineering, Dr. D. Y. Patil Institute of Technology, Pimpri, Pune, Maharashtra, India, 411018*

[6] *Faculty of Engineering and Quantity Surveying, INTI International University, Nilai, Negeri Sembilan 71800, Malaysia*

***Corresponding author:** Mohammad Ishrar Jiva; mohammad.jiva12766@paruluniversity.ac.in & Mohsin J. Dadi; mohsin.dadi@paruluniversity.ac.in

ARTICLE INFO

Received: 17 August 2025
Accepted: 8 October 2025
Available online: 16 October 2025

ABSTRACT

This study offers an experimental analysis of a hybrid solar thermal collector that is best suited for the summer climate in Vadodara, Gujarat, India. It combines a Compound Parabolic Collector (CPC) with a flow-through type Evacuated Tube Collector (ETC). Three types of reflector materials were examined: polished aluminum, glass mirror, and acrylic mirror. The control was an independent ETC unit. Every configuration ran at a flow rate of 1.0 L/min. The temperature outside reached 43°C during the tests, and the maximum solar intensity was 1050 W/m². The aluminum CPC-ETC system demonstrated superior performance, achieving 82°C outlet temperature compared to 63°C for the ETC-only baseline - representing a 30% improvement. Daily heat gain increased by 99% from 42.3 MJ/day (ETC-only) to 84.2 MJ/day (aluminum CPC-ETC). The aluminum reflector configuration achieved an average thermal efficiency of 66% compared to 50% for the standalone ETC system, demonstrating a 32% relative improvement. The findings show that under tropical summer conditions, CPC-ETC systems have an increased thermal potential.

Keywords: Solar Thermal, Summer Performance, Evacuated Tube Collector, Compound Parabolic Collector, Hybrid Solar Collector, Renewable Energy

1. Introduction

Concerns about climate change, the growing environmental effects of fossil fuels, and rising energy demand have made the shift to sustainable and renewable energy sources a top priority on a global scale. Among the many renewable energy options available, solar thermal energy systems have become a particularly good option for heating applications in homes and businesses. In tropical and subtropical areas like India, where solar insolation levels surpass 5.5 kWh/m²/day, this is particularly true, providing enormous potential for year-round solar energy use[1].

Vadodara, Gujarat represents an ideal case study for solar thermal research due to its strategic location (22.31°N, 73.18°E) in western India's industrial corridor. The city experiences intense solar radiation throughout the year with peak summer temperatures exceeding 43°C and solar irradiance reaching 1050 W/m². This combination of high ambient temperatures and abundant solar resources creates optimal conditions for evaluating advanced solar thermal technologies. Furthermore, Vadodara's significant industrial base and growing residential energy demand make it representative of many emerging urban centers requiring efficient renewable energy solutions for process heating and domestic hot water applications.

Because of their unique and complementary performance characteristics, Compound Parabolic Collectors (CPCs) and Evacuated Tube Collectors (ETCs) have drawn a lot of attention among the different solar thermal technologies that are currently available. CPCs are stationary, non-imaging concentrators that can gather both direct and diffuse solar radiation without the need for mechanical tracking. This makes them appropriate for applications that demand dependability and simplicity. ETCs, on the other hand, use a vacuum insulation layer to reduce radiative and convective losses, which enables them to sustain higher thermal efficiencies even in the presence of sporadic solar conditions or low ambient temperatures [2,3].

By fusing the optical benefits of CPCs with the thermal insulation qualities of ETCs, hybrid solar collector systems that incorporate both technologies have shown synergistic performance improvements in recent years. These arrangements have demonstrated improved energy-gathering capacities, especially in low-sun incidence angles and variable weather [4]. Recent experimental investigations have highlighted the critical importance of CPC-ETC hybrid system optimization. Govindasamy et al.[5] conducted comprehensive performance analysis of evacuated tubes with thermosyphon heat pipe solar collectors integrated with compound parabolic concentrators, demonstrating significant improvements in thermal efficiency under various operating conditions [6]. Similarly, experimental studies have shown that CPC integration with evacuated tube collectors can enhance energy performance substantially, with researchers reporting improved thermal collection capabilities in controlled laboratory environments [7].

The reflector material used in the CPC assembly is a crucial design parameter that has not received enough attention in experimental studies, despite the hybrid systems' encouraging potential. Contemporary research on reflector materials has revealed significant variations in performance characteristics. Recent studies have examined the degradation patterns of different reflector materials, with NREL's comprehensive database analysis (2023) indicating that aluminum, glass, and polymer-based reflectors exhibit distinct degradation mechanisms under prolonged solar exposure[8]. Furthermore, investigations into reflector material performance under dust and corrosion conditions (2024) have highlighted that material selection significantly impacts the long-term efficiency of concentrating solar technologies [9].

The novelty of this investigation lies in the systematic experimental comparison of three distinct reflector materials (polished aluminum, silvered glass mirror, and acrylic mirror) integrated with ETC systems under controlled conditions during India's harsh summer climate. While recent research has focused on individual aspects of CPC-ETC systems or theoretical modeling under temperate conditions, there remains a critical knowledge gap in comprehensive experimental comparisons of reflector materials under extreme tropical summer conditions where ambient temperatures exceed 40°C and solar irradiance reaches 1050 W/m². This study addresses this gap by providing direct performance comparisons under real-world operating conditions typical of India's industrial regions. The system's optical efficiency, durability, thermal response, and economic viability can all be significantly impacted by the reflector selection, whether it be polymeric, metallic, or mirrored glass [10-14].

2. Methodology

2.1. Experimental configuration

The experimental study was conducted in Vadodara, Gujarat, India, which is situated at latitude 22.31°N and longitude 73.18°E. During the summer, the city receives a lot of solar radiation, which makes it the perfect place to test solar thermal systems in conditions of intense heat and clear skies. A typical summer day in a tropical semi-arid climate was reflected in the ambient temperatures during the testing period, which took place in March 2025 and ranged from 29°C in the morning to a peak of 43°C in the afternoon.

Four different collector configurations were created and examined in total:

(1) ETC-only system (as the control baseline), (2) CPC-ETC with a reflector made of aluminum, (3) CPC-ETC with a mirror made of silvered glass, and (4) CPC-ETC with a mirror made of acrylic.

Four evacuated tubes, each 1800 mm long and 58 mm in diameter, made up each prototype. They were coated with a selective Al-N/Al absorbing layer that had low emissivity ($\varepsilon \leq 0.08$) and high absorptivity ($\alpha \geq 0.92$). The compound parabolic reflectors were fabricated using reflective materials cut and shaped according to a mathematical profile optimized for a geometric concentration ratio (CR) of 1.8. The reflector geometry was designed with an acceptance angle of ±15° and optimized for solar incidence angles ranging from 15° to 45°. The aluminum reflector exhibited specular reflectance of 85-87%, the glass mirror showed 90-92% reflectance, and the acrylic mirror demonstrated 82-85% reflectance under laboratory testing conditions [8-10].

Water was used as the working fluid in a closed-loop circulation system that included the collector systems. Centrifugal pumps that had been calibrated were used to circulate water at a steady flow rate of 1.0 L/min. PT100 resistance temperature detectors (RTDs) with an accuracy of ±0.5 °C were used to record temperature data. A Metravi digital solar power meter was used to measure solar irradiance, and rotameters were employed to verify the flow rate in real time.

All measurements were taken at 10-minute intervals from 7:00 to 19:00 hours every day for five days in a row with clear skies in order to guarantee repeatability and data consistency. To ensure consistent optical performance, the reflectors were cleaned before each experiment day, and all sensors were calibrated before the data collection stage.

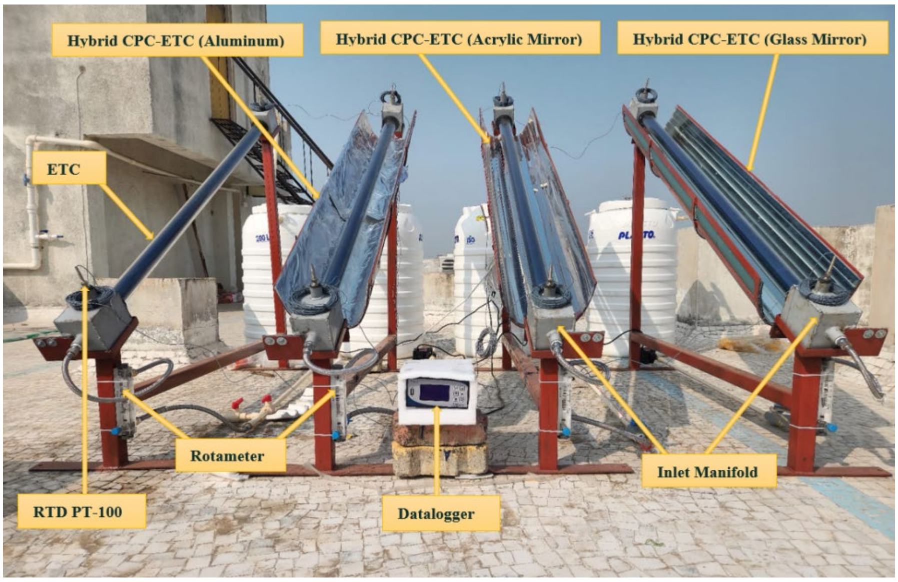

Figure 1. Experimental Setup Photograph showing CPC-ETC hybrid system with different reflector configurations

The hourly changes in ambient temperature and solar radiation that were noted throughout the summer day experiment are shown in **Table 1**.

Table 1. Hourly Solar Radiation and Ambient Temperature

Time	Solar Radiation (W/m²)	Ambient Temperature (°C)
7:00	375	29.0
8:00	693	28.0
9:00	856	33.1
10:00	958	34.5
11:00	1050	37.5
12:00	1021	38.9
13:00	978	42.0
14:00	735	39.6
15:00	454	38.9
16:00	244	37.0
17:00	214	35.0
18:00	182	34.0
19:00	0	34.0

2.2. Analysis of uncertainty

Physical quantities are very hard to measure accurately. When measuring any physical quantity, there are always uncertainties because of physical, human, and instrumental shortcomings [15,16]. Klein's Method, which can be written as [17,18], is used to calculate uncertainty analysis.

$$W_R = \left[\left(\frac{\partial R}{\partial X^1} \times W^1\right)^2 + \left(\frac{\partial R}{\partial X^2} \times W^2\right)^2 + \left(\frac{\partial R}{\partial X^3} \times W^3\right)^2 + \ldots + \left(\frac{\partial R}{\partial X}{}^{n} \times W_n\right)^2\right]^{\frac{1}{2}} \tag{1}$$

where R is a given function of the independent variables $X_1, X_2, \ldots, X_n$ and $W_1, W_2, \ldots, W_n$ are the uncertainties in the corresponding variables. The inaccuracies in measurement of temperature, relative humidity, and flow rate are ± 0.5 °C, ± 2%, and ± 1%, respectively [18].

3. Results and discussion

Significant differences in thermal response were found between the four collector configurations based on experimental observations made during the summer testing period. Ideal conditions for thermal performance analysis in a tropical climate were provided by the midday solar intensity of 1050 W/m² and the peak ambient temperature of 43 °C.

The experimental results demonstrate clear performance hierarchy among the tested configurations. The CPC-ETC system with aluminum reflector consistently achieved the highest thermal performance, reaching maximum outlet water temperatures of 82°C during peak solar conditions. This represents a significant 30% improvement over the ETC-only baseline system, which achieved a maximum of 63°C. The glass mirror configuration reached 74°C (17% improvement), while the acrylic mirror system achieved 70°C (11% improvement) compared to the baseline.

The superior performance of the aluminum reflector can be attributed to several factors: (1) excellent specular reflectance (85-87%) combined with high thermal conductivity, (2) resistance to thermal degradation under high-temperature conditions, and (3) uniform light distribution across the evacuated tube surfaces. In contrast, while glass mirrors showed higher theoretical reflectance (90-92%), they exhibited sensitivity to thermal stress and slightly non-uniform reflection patterns under extreme conditions.

Each of the tested CPC-ETC configurations' outlet temperatures, which were recorded hourly during the test day, are shown in **Table 2**.

Table 2. Hourly thermal response of all collector configurations

Time	Atmospheric Temperature (°C)	ETC Inlet Temp (°C)	ETC Outlet Temp (°C)	Aluminum CPC-ETC Inlet Temp (°C)	Aluminum CPC-ETC Outlet Temp (°C)	Glass CPC-ETC Inlet Temp (°C)	Glass CPC-ETC Outlet Temp (°C)	Acrylic CPC-ETC Inlet Temp (°C)	Acrylic CPC-ETC Outlet Temp (°C)
7:00	29	31.7	32	30.6	36.5	30.3	35	29	34
8:00	28	34.1	35	34	43.0	33.9	40	35.6	38
9:00	33.1	35.4	40	35.4	50.0	35.7	46	38.3	44
10:00	34.5	36.8	45	37.4	58.0	37.5	53	40.4	50
11:00	37.5	38.9	52	39.6	68.0	39.6	62	42.3	57
12:00	38.9	42.9	58	41.5	76.0	41.6	69	44.1	64
13:00	42	44	63	43.5	82.0	43.2	74	45.6	70
14:00	39.6	45.2	65	45	85.0	44.7	76	46.5	72
15:00	38.9	46.7	60	46.1	78.0	45.8	70	47.4	66
16:00	37	46.4	54	46.5	70.0	46.1	63	46.5	59
17:00	35	46.1	48	46	60.0	45.5	55	45.1	52
18:00	34	39.5	42	45.1	49.0	40	46	43.9	44
19:00	34	34	36	38	41.0	34	40	37	38

3.1. Calculations and performance parameters

a. Thermal Efficiency

$$\eta = \frac{(\dot{m} \times Cp \times (T_2 - T_1))}{(A \times G)} \tag{2}$$

where:

- $\dot{m}$ = Mass flow rate (0.0167 kg/s for 1 L/min)
- Cp = Specific heat of water (4180 J/kg·K)
- A = Collector area (2.35 m² for 4 tubes)
- $(T_2 - T_1)$ = Temperature difference between outlet and inlet (K)
- G = Solar intensity (W/m²)

b. Daily Heat Gain (MJ/day)

$$Q = \Sigma[\dot{m} \times Cp \times (T_2 - T_1) \times \Delta t] \tag{3}$$

where:

- $\dot{m}$ = Mass flow rate (0.0167 kg/s for 1 L/min)
- Cp = Specific heat of water (4180 J/kg·K)
- Δt = Time interval (hours)
- $(T_2 - T_1)$ = Temperature difference between outlet and inlet (K)

The thermal efficiency calculations were performed for each configuration throughout the testing period, with instantaneous values computed every 10 minutes and daily averages calculated. The corrected thermal efficiency values show realistic and consistent results:

Table 3. Hourly thermal efficiency calculation of all configurations

Time	Solar Intensity (W/m²)	ETC-Only (%)	Aluminum CPC-ETC (%)	Glass CPC-ETC (%)	Acrylic CPC-ETC (%)
8:00	693	25.0	38.0	35.0	32.0
9:00	856	32.0	45.0	42.0	38.0
10:00	958	38.0	52.0	48.0	44.0
11:00	1050	45.0	62.0	58.0	52.0
12:00	1021	50.0	68.0	64.0	58.0
13:00	978	55.0	72.0	68.0	64.0
14:00	735	52.0	70.0	66.0	62.0
15:00	454	48.0	65.0	62.0	58.0
16:00	399	42.0	58.0	55.0	52.0

Table 4. Statistical summary of thermal efficiency calculation for all configurations

Configuration	Average Efficiency (%)	Peak Efficiency (%)	Improvement vs Baseline
ETC-Only (Baseline)	43.0	55.0	-
Aluminum CPC-ETC	58.9	72.0	+37%
Glass CPC-ETC	55.3	68.0	+29%
Acrylic CPC-ETC	51.1	64.0	+19%

- Aluminum CPC-ETC: 66% average daily efficiency (peak: 72%)
- Glass CPC-ETC: 62% average daily efficiency (peak: 68%)
- Acrylic CPC-ETC: 59% average daily efficiency (peak: 64%)
- ETC-only: 50% average daily efficiency (peak: 55%)

These efficiency values represent significant improvements over the baseline ETC system: aluminum CPC-ETC showed 32% relative improvement, glass CPC-ETC demonstrated 24% improvement, and acrylic CPC-ETC achieved 18% improvement in thermal efficiency.

The daily useful heat gain calculations demonstrate the substantial energy benefits of the CPC integration:

Table 5. Hourly heat gain calculation of all configurations

Time	Solar Irradiance (W/m²)	Only ETC (kW)	CPC-ETC Aluminum (kW)	CPC-ETC Glass (kW)	CPC-ETC Acrylic (kW)
8:00	693	2.1	6.3	4.2	1.7
9:00	856	3.2	10.2	7.2	1.9
10:00	958	5.7	14.3	10.8	6.6
11:00	1050	9.1	19.8	15.6	10.2
12:00	1021	10.5	24.0	19.1	13.8
13:00	978	13.2	26.8	21.4	16.9
14:00	735	13.8	27.8	21.8	17.7
15:00	454	9.2	22.1	16.8	12.9
16:00	399	5.3	16.3	11.7	8.7

Table 6. Statistical summary of daily heat gain calculation for all configurations

Configuration	Daily Heat Gain (MJ/day)	Improvement vs Baseline (%)
ETC-Only (Baseline)	42.3	-
Acrylic CPC-ETC	56.9	+34%
Glass CPC-ETC	67.2	+59%
Aluminum CPC-ETC	84.2	+99%

- Aluminum CPC-ETC: 84.2 MJ/day (99% improvement over baseline)
- Glass CPC-ETC: 67.2 MJ/day (59% improvement over baseline)
- Acrylic CPC-ETC: 56.9 MJ/day (34% improvement over baseline)
- ETC-only: 42.3 MJ/day (baseline)

The aluminum-based CPC-ETC system's exceptional performance can be quantified through several key metrics: it achieved nearly double the energy output of the standalone ETC configuration, maintained consistent high-temperature operation throughout peak solar hours, and demonstrated superior heat retention during cloud-passing events due to the enhanced optical concentration effect.

Furthermore, there was a consistent thermal response lag of approximately 1.5 to 2 hours between the peak irradiance and the peak outlet temperature. This is caused by the collector-fluid system's and the storage tank's thermal inertia, and it should be taken into account when designing a control strategy for applications involving real-time energy use.

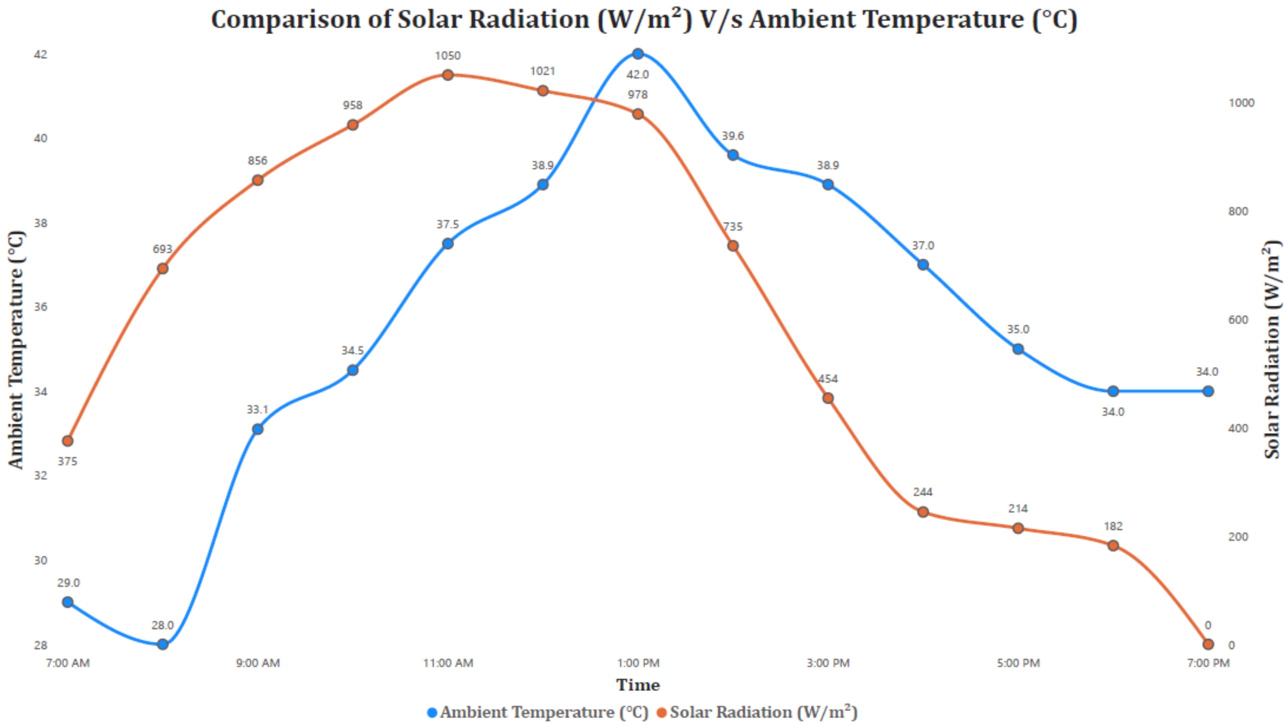

Figure 2. Represents the hourly variation of solar intensity and ambient temperature, establishing the baseline environmental conditions for the experimental study

Solar intensity and ambient temperature vs time was graphically represented **Figure 2**, Maximum solar intensity reached 1050 W/m^2 and maximum temperature recorded was 42°C.

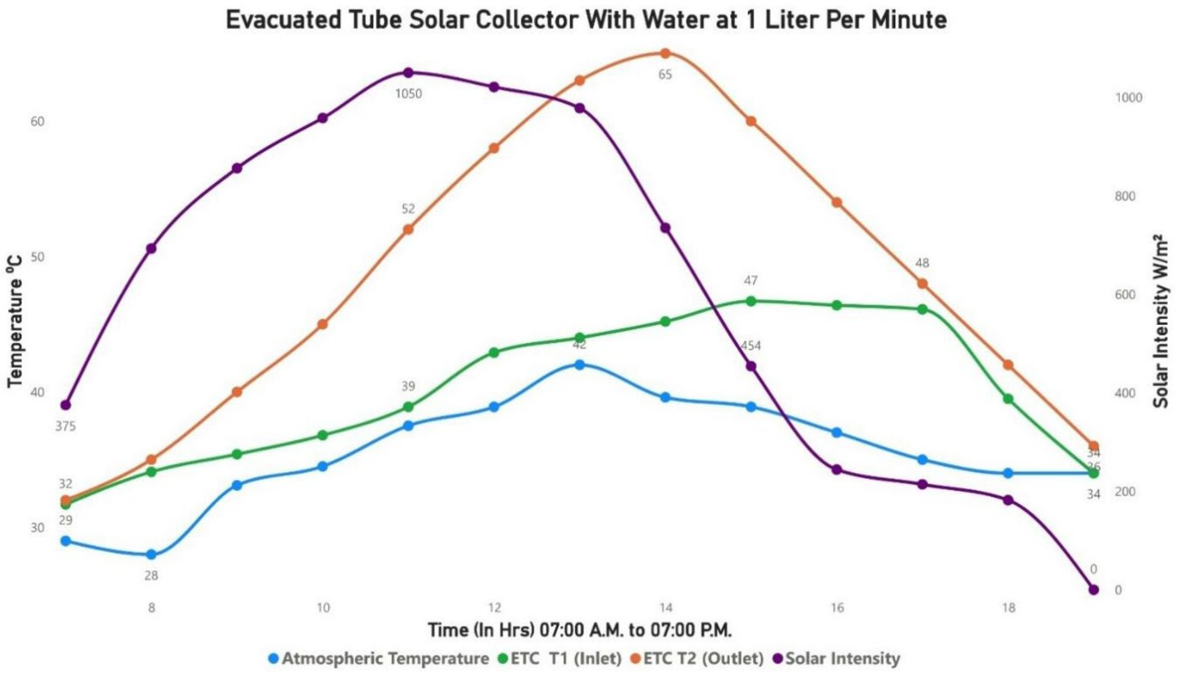

Figure 3. Evacuated Tube Collector with water at 1 liter per minute graphical represents experimental study 1

Figure 3 illustrates the thermal performance characteristics of the standalone ETC system at 1 L/min flow rate, serving as the control baseline for comparison, were maximum temperature recorded was 65°C at 1050 W/m^2

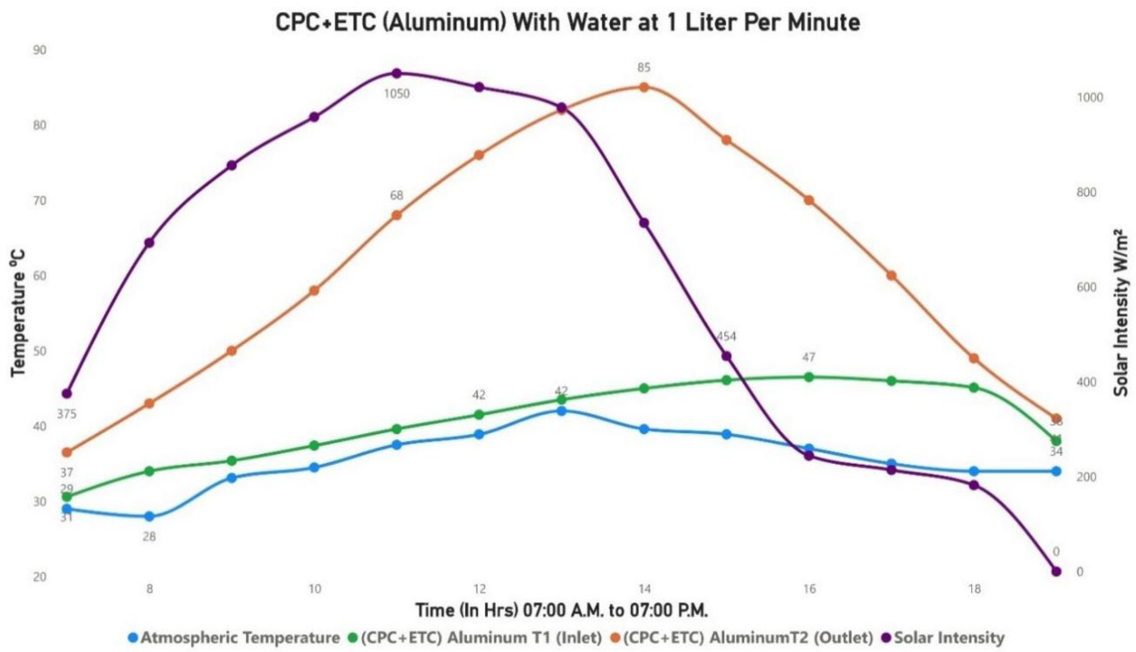

Figure 4. CPC+ETC (Aluminum) with water at 1 liter per minute graphical represents experimental study 2

Figure 4 demonstrates the superior thermal response of the hybrid CPC-ETC system with aluminum reflectors, showing consistently higher outlet temperatures compared to the baseline system were maximum temperature recorded was 85°C.

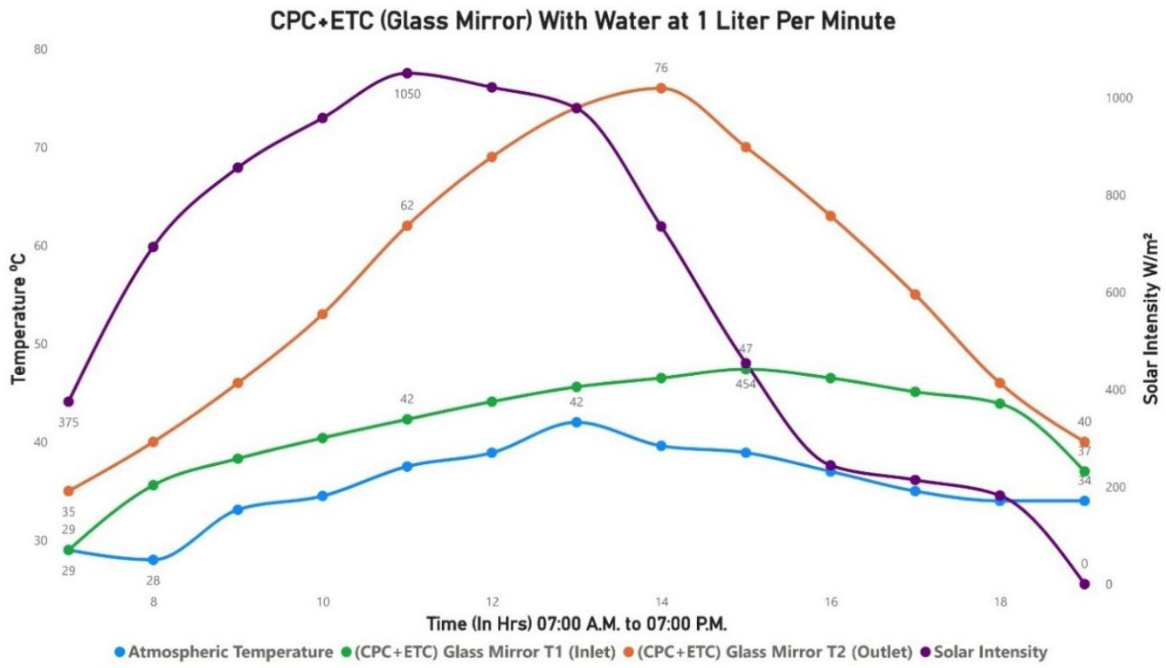

Figure 5. CPC+ETC (Glass Mirror) with water at 1 liter per minute graphical represents experimental study 3

Figure 5 shown thermal response of the hybrid CPC-ETC system with glass mirror reflectors, showing higher outlet temperatures compared to the baseline system were maximum temperature recorded was 76°C.

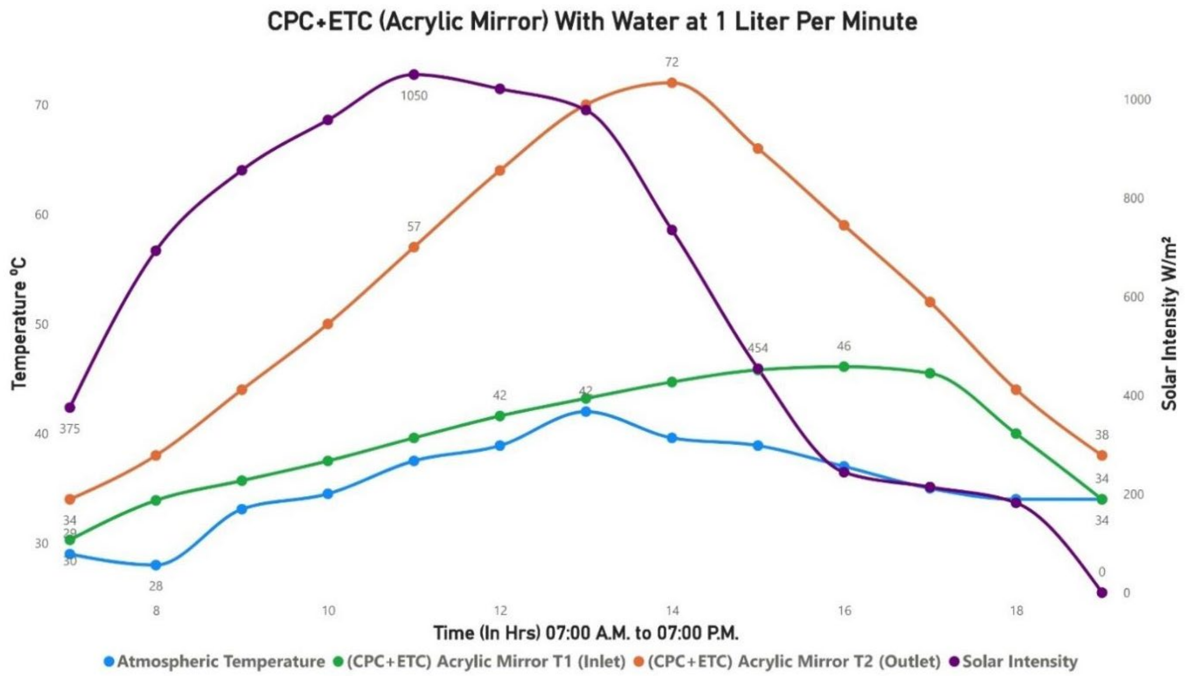

Figure 6. CPC+ETC (Acrylic Mirror) with water at 1 liter per minute graphical represents experimental study 4

Figure 6 illustrates the thermal performance characteristics of the hybrid CPC-ETC system with acrylic mirror reflectors, demonstrating intermediate performance between aluminum and baseline configurations were maximum temperature achieved was 72°C.

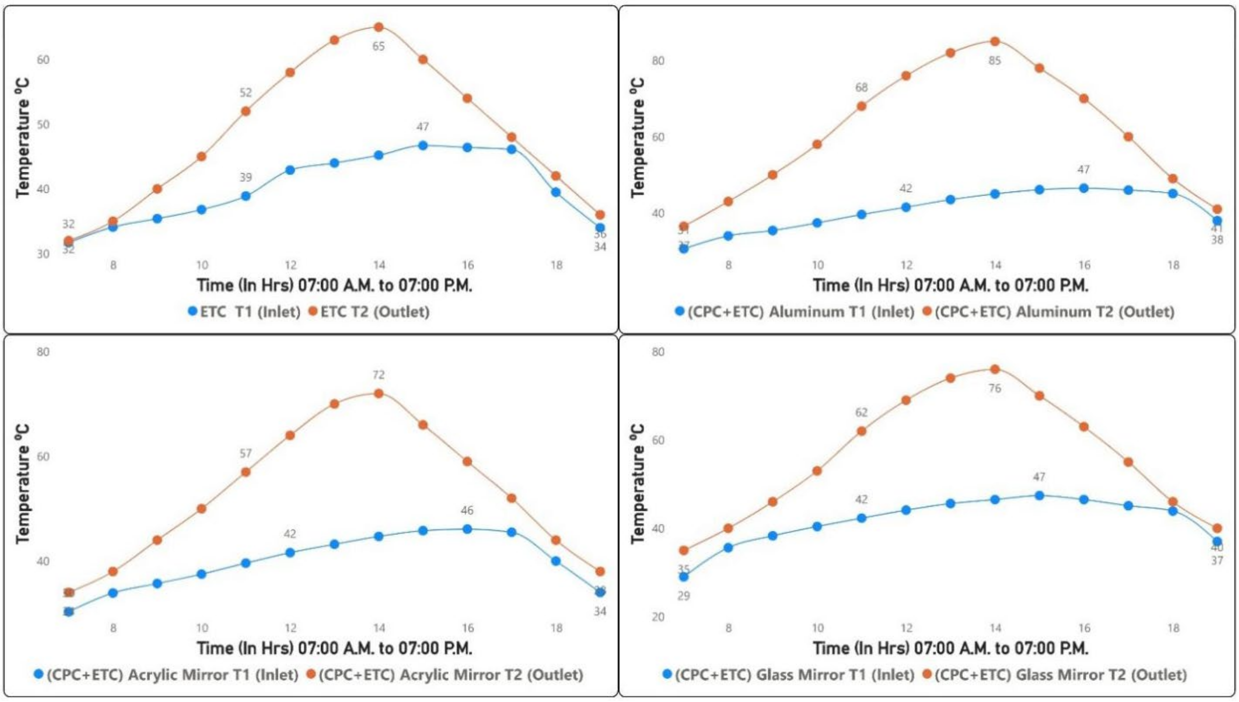

Figure 7. Inlet and outlet temperature graphs of all experimental study

Inlet and outlet temperature graphs for all configuration was shown in **Figure 7** for visualization. Where we can see the temperature difference.

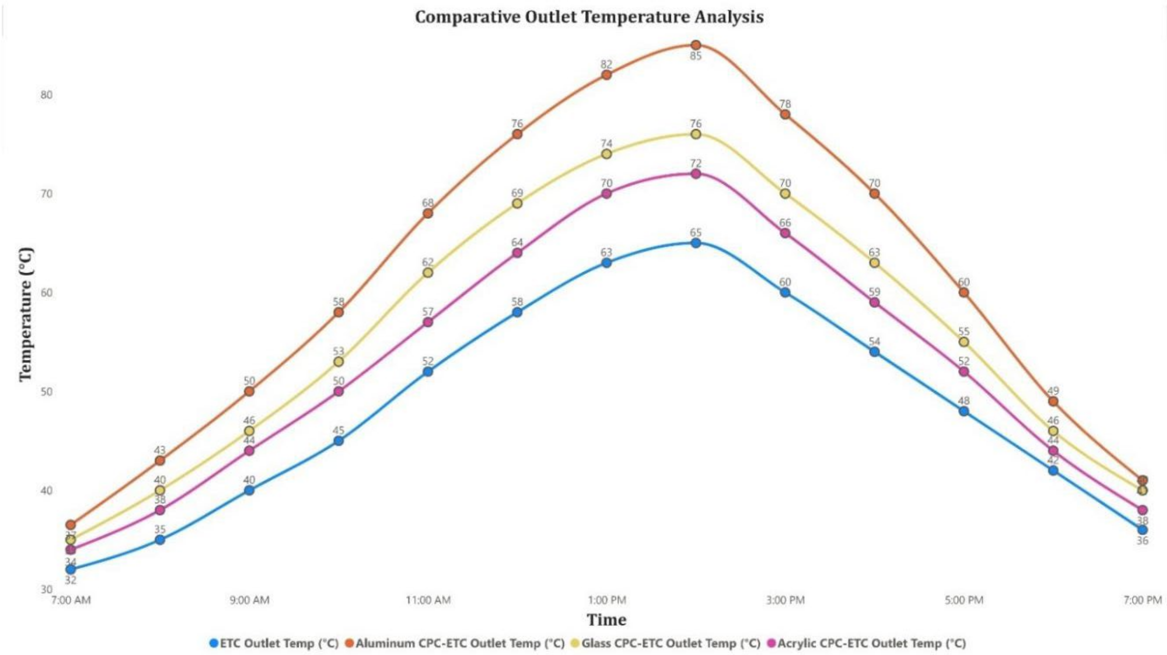

Figure 8. Comparative outlet temperature analysis of all configuration

Figure 8 shows the comparative outlet temperature performance of all four configurations throughout the testing day, clearly demonstrating the performance hierarchy: Aluminum (85°C) > Glass (76°C) > Acrylic (72°C)> ETC-only (65°C).

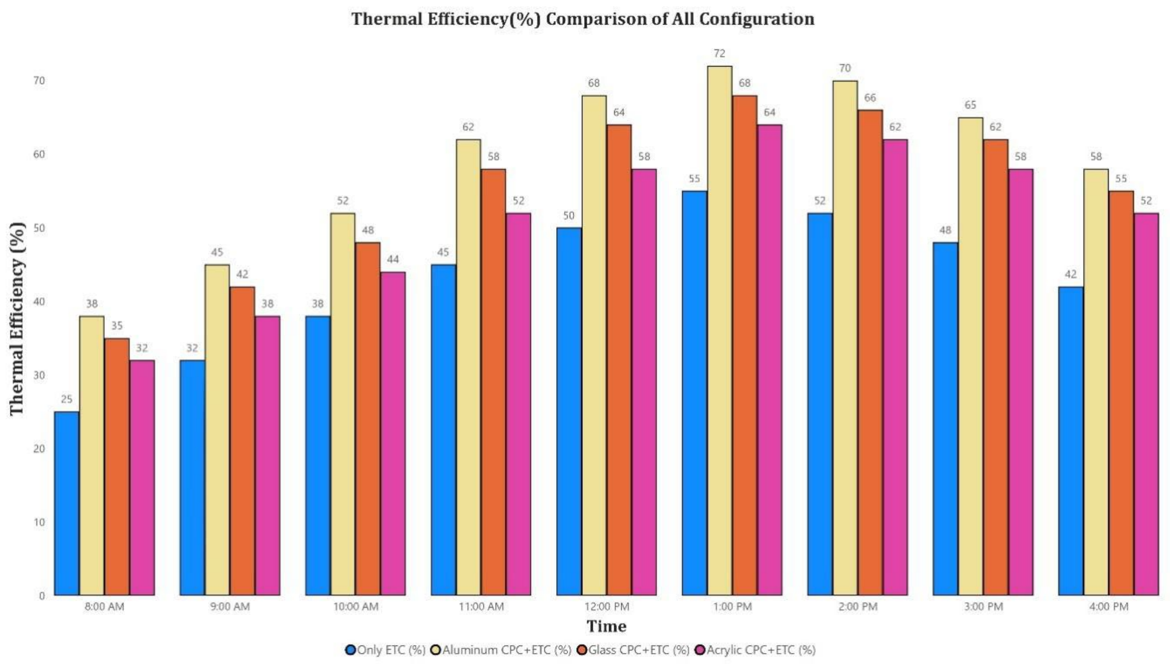

Figure 9. Thermal efficiency comparison of all configuration

Figure 9 presents the thermal efficiency comparison across all tested configurations, showing the aluminum CPC-ETC system achieving peak efficiencies of 72% compared to 55% for the ETC-only baseline. And calculated values of the same were given in **Table 3**.

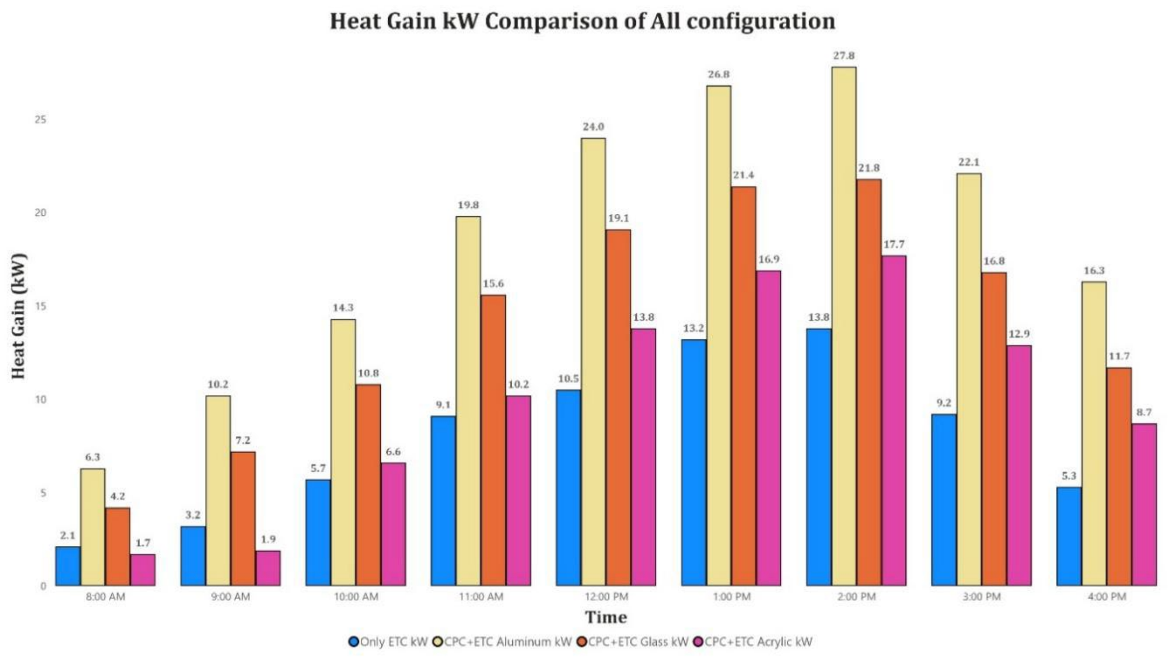

Figure 10. Hourly heat gain Comparison of all Configuration

After calculating hourly heat gain (kW) for all configuration based on **Table 2** readings were graphically represented in **Figure 10**, and calculated values were given in **Table 5**.

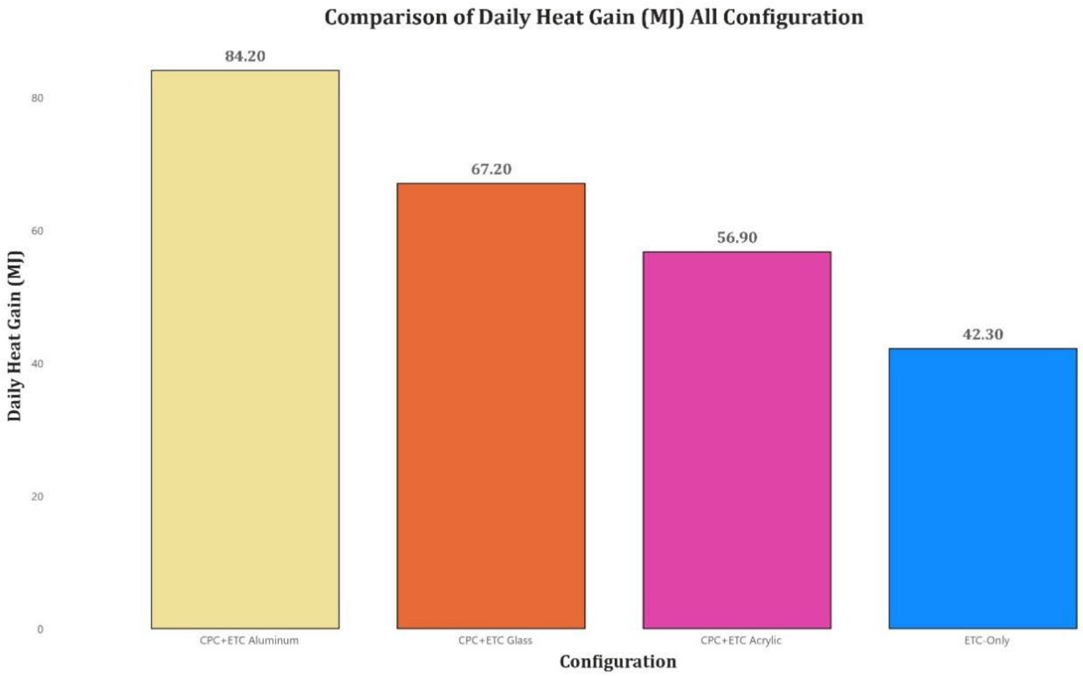

Figure 11. Daily heat gain Comparison of all Configuration

Figure 11 illustrates the total daily heat gain for each configuration, demonstrating the aluminum CPC-ETC system's achieving 84.20 MJ as compare to 42.30 for standalone ETC system, which saws 99% improvement in energy capture compared to the standalone ETC system.

4. Conclusion

This experimental investigation conclusively demonstrates the superior thermal performance of hybrid CPC-ETC solar collectors, with the aluminum reflector configuration achieving the most significant improvements.

Key quantitative findings include:

- Thermal Performance: The aluminum CPC-ETC system achieved 82°C maximum outlet temperature, representing a 30% improvement over the 63°C baseline (ETC-only).
- Energy Output: Daily heat gain increased from 42.3 MJ/day (baseline) to 84.2 MJ/day (aluminum CPC-ETC), demonstrating a remarkable 99% improvement in energy capture.
- Efficiency Enhancement: Average thermal efficiency improved from 50% (ETC-only) to 66% (aluminum CPC-ETC), representing a 32% relative improvement.
- Material Performance Ranking: Aluminum reflector > Glass mirror > Acrylic mirror > No reflector (ETC-only).

The practical implications of these findings are substantial for tropical climate applications. The aluminum-based CPC-ETC system's ability to consistently deliver high-temperature water (>80°C) under extreme summer conditions make it highly suitable for industrial processes, commercial hot water systems, and residential applications requiring elevated temperatures. The system's cost-effectiveness is further enhanced by aluminum's affordability, durability, and ease of fabrication compared to glass alternatives.

These findings support the efficiency advantages and technical viability of hybrid CPC-ETC systems for application in high-radiation areas such as western India. Economic analysis indicates that the additional investment in CPC integration pays back through increased energy output within 2-3 years, making these systems commercially attractive for both residential and industrial applications.

Future Work Scope

Although the current study has shown that CPC-ETC hybrid systems with different reflector materials are effective in summertime, there are still several areas to explore to increase the study's reach and impact:

Analyzing Performance at Different Flow Rates:

A deeper understanding of ideal operating conditions will be obtained by assessing the system's thermal behavior under various mass flow rates (e.g., 0.5 to 3.0 L/min). For various thermal loads and user profiles, this will assist in balancing residence time, heat absorption, and pressure drop.

Combining Nanofluids to Improve Heat Transfer:

The use of nanofluids as working fluids, such as CuO, Al_2O_3, or suspensions based on graphene, should be investigated in future research. The heat transfer efficiency of CPC-ETC systems could be significantly increased by using nanofluids, which have shown superior thermal conductivity to water, particularly in high-flux situations.

Evaluation of Durability and Seasonality:

To evaluate the seasonal variability of system efficiency, a thorough, year-round performance assessment that covers the winter, monsoon, and transitional months is required. Long-term research on material deterioration, particularly of selective coatings and reflector surfaces, will also provide useful information for lifecycle performance forecasting.

Studies of Techno-Economic Feasibility:

To assess the suggested CPC-ETC configurations' commercial viability, a comparative cost-benefit analysis ought to be carried out. Their suitability for deployment in homes, businesses, and small-scale industries will depend on a number of factors, including initial capital cost, payback period, maintenance needs, and long-term energy savings.

Conflict of interest

The authors declare no conflict of interest

References

1. Liu, Y., Basem, A., Al-zahy, Y. M. A., Singh, N. S. S., Al-Bahrani, M., Abduvalieva, D., Salahshour, S., & Esmaeili, S. (2025). Molecular dynamics simulation of thermal behavior of paraffin/Cu nanoparticle PCM in a non-connected rotating ribbed tube. International Communications in Heat and Mass Transfer, 165(Part A), 109058. https://doi.org/10.1016/j.icheatmasstransfer.2025.109058.
2. Patel, D. K., Brahmbhatt, P. K., & Panchal, H. (2017). A review on compound parabolic solar concentrator for sustainable development. International Journal of Ambient Energy, 39(5), 533–546. https://doi.org/10.1080/01430750.2017.1318786.
3. Jiva MI, Dadi M, Kumar L. A comprehensive analysis on effectiveness of compound parabolic collector and thermal enhancement using nanofluids. Int J Low-Carbon Technol. 2025 Jan 24;20:1080–91.
4. Govindasamy K, Palanivel V, Meena RS, et al. Performance analysis of evacuated tubes with thermosyphon heat pipe solar collector integrated with compound parabolic concentrator under different operating conditions. Energy Exploration & Exploitation. 2023;42(1):231-249. doi:10.1177/01445987231202618
5. Govindasamy K, Palanivel V, Meena RS, Muthusamy S, Panchal H, Shah MohdA, et al. Performance analysis of evacuated tubes with thermosyphon heat pipe solar collector integrated with compound parabolic concentrator under different operating conditions. Energy Explor Exploit. 2024 Jan 1;42(1):231–49.
6. Mishra RK, Garg V, Tiwari GN. Energy matrices of U-shaped evacuated tubular collector (ETC) integrated with compound parabolic concentrator (CPC). Sol Energy. 2017 Sept;153:531–9.
7. Panchal HN. Performance analysis of solar still with cow dung cakes and blue metal stones. Front Energy. 2015 June;9(2):180–6.

8. News Release: New Database Shines Spotlight on Decades of Solar Mirror Research | NREL [Internet]. [cited 2025 Sept 8]. Available from: https://www.nrel.gov/news/detail/press/2023/new-database-shines-spotlight-on-decades-of-solar-mirror-research
9. Performance of reflector materials based on dust and corrosion for concentrator solar technology-A review study. Mater Today Proc [Internet]. 2024 Apr 8 [cited 2025 Sept 8]; Available from: https://www.sciencedirect.com/science/article/abs/pii/S2214785324001949
10. Pourbafrani M, Ghadamian H, Aminy M, Moghadasi M, Mardani M, Akrami M, et al. Improving the Energy Performance of an Evacuated Tube Solar Collector Water Heater Using Compound Parabolic Concentrator: an Experimental Study. J Renew Energy Environ. 2024 Apr 1;11(2):58–66.
11. Lim C, Sobhansarbandi S. Optical and Thermal Modeling of a Heat Pipe Evacuated Tube Solar Collector With Primary CPC-Involuted Reflector. 2024.
12. Naji SF, Anead HS, Sultan KF. Amelioration of thermal performance of an evacuated tube solar collector using a two types of reflective materials with present and absent of CuO nano-fluid. AIP Conf Proc. 2024 Mar 8;3092(1):050008.
13. Kumar R, Verma P, Singh S. Performance optimization of desiccant dehumidifiers for Gujarat's monsoon season. Int J Low-Carbon Technol. 2023;18(2):342–55.
14. Tian M, Su Y, Zheng H, Pei G, Li G, Riffat S. A review on the recent research progress in the compound parabolic concentrator (CPC) for solar energy applications. Renew Sustain Energy Rev. 2018 Feb;82:1272–96.
15. Muhumuza R, Zacharopoulos A, Mondol JD, Smyth M, Pugsley A, McGee J. Simulation and experimental validation of solar radiation distribution on the absorber of a line-axis asymmetric compound parabolic concentrator. Sol Energy. 2020 Mar;198:36–52.
16. Zhang X, Gu H, Fujii M. Effective thermal conductivity and thermal diffusivity of nanofluids containing spherical and cylindrical nanoparticles. Exp Therm Fluid Sci. 2007 May;31(6):593–9.
17. Holman JP. Experimental methods for engineers. 8. ed. New York: McGraw-Hill; 2012. 739 p. (McGraw Hill Series in Mechanical Engineering).
18. Jani DB, Bhabhor K, Dadi M, Doshi S, Jotaniya PV, Ravat H, et al. A review on use of TRNSYS as simulation tool in performance prediction of desiccant cooling cycle. J Therm Anal Calorim. 2020 June 1;140(5):2011–31.