

THERMAL ANALYSIS OF PARABOLIC TROUGH SOLAR COLLECTOR SYSTEM FOR WATER HEATING

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ABSTRACT

We are contributors to environmental pollution, that's why it is our collective responsibility to remain aware of environmental issues. We should move towards the adoption of green energy sources for thermal energy to reduce dependence on conventional fossil fuels and associated environmental impacts. Solar thermal energy is a clean and renewable alternative that can contribute to sustainable energy utilization, particularly for water heating applications. Among solar thermal technologies, the parabolic trough solar collector (PTSC) is an effective system for concentrating solar radiation and converting it into useful thermal energy. This study focuses on the thermal analysis and working principle of a parabolic trough solar collector system for water heating under the climatic conditions of Indore, Madhya Pradesh. A PTSC prototype was designed and fabricated to investigate its thermal performance under actual outdoor solar conditions. The working principle involves concentrating incident solar radiation onto a receiver tube positioned along the focal line of the parabolic reflector, where the absorbed solar energy is transferred to flowing water. The thermal analysis evaluates the effects of three different water flow rates on outlet temperature, useful heat gain, and thermal efficiency. A theoretical thermal performance model based on the Hottel–Whillier–Bliss approach was developed and compared with experimental measurements. Regression analysis and ANOVA were also employed to evaluate performance trends and identify suitable operating conditions. The findings demonstrate the potential of PTSC technology as an efficient and sustainable solution for domestic water heating.

Keywords: Solar Energy¹, Parabolic Trough Solar Collector², Water Heating³, Thermal Efficiency⁴, Hottel-Whillier-Bliss Model⁵.

1. Introduction

The growing energy demand of industrial, commercial, and domestic sectors has largely been met through fossil fuel combustion, which contributes significantly to greenhouse gas emission and global warming [1]. Solar energy stands out among renewable resources because it is abundant, freely available, and produces no direct emissions during conversion [2]. Solar technologies are broadly classified as active or passive depending on whether external components such as pumps, fans, or controllers are required to move the working fluid [1], [3]. Solar collectors are further categorized according to the type of energy delivered (thermal or non-thermal) and the mode of collection (concentrated or non-concentrated), as illustrated in Figure 1.

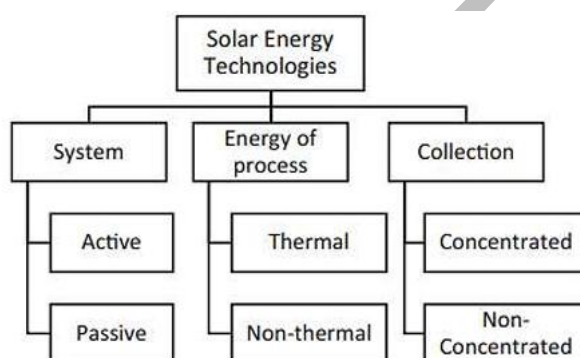


Figure 1. Classification of solar energy technologies [1].

Among the concentrating solar technologies compound parabolic collectors, linear Fresnel reflectors, solar dish systems, solar towers, and parabolic trough collectors the parabolic trough solar collector (PTSC) is the most commercially mature and widely deployed, accounting for the majority of installed concentrated solar power (CSP) capacity worldwide [4], [5]. The PTSC concentrates direct normal irradiance (DNI) using a curved, U-shaped reflective surface onto a receiver tube running along its focal line, heating a working fluid that flows through it [6]. While large-scale PTSC plants typically use thermal oil or molten salt to drive steam turbines for electricity generation [7], smaller PTSC units can be adapted for low- and medium-temperature applications such as domestic and industrial water heating, which is the focus of the present study.

Water heating using solar thermal collectors offers a practical route to reduce electricity and LPG consumption in households, especially in regions such as Indore, Madhya Pradesh, which receive high annual solar insolation [8]. Unlike flat plate collectors, PTSCs achieve higher outlet temperatures because of their concentrating geometry, making them attractive even for relatively compact, low-cost residential systems [9]. However, the thermal performance of a PTSC used for water heating is sensitive to several operating and design parameters, including flow rate, receiver tube material, reflector reflectivity, and ambient conditions [10]. This motivates a combined experimental and theoretical thermal analysis, of the type undertaken in this study.

1.1 Components of PTSC

A parabolic trough solar collector consists of four main components: the parabolic reflector, the receiver tube, the support structure, and the sun-tracking mechanism [1], [6].

- **Parabolic Reflector:** A curved reflective sheet, usually made of silvered glass, anodized aluminum, or a silvered polymer film, bent into a parabolic profile. It must possess high specular reflectivity so that all incoming parallel solar rays converge onto the focal line [11].
- **Receiver Tube:** Positioned along the focal line, the receiver tube is generally a metal tube (copper or stainless steel) coated with a selective absorber layer, surrounded by an evacuated or air-filled glass envelope to minimize convective and radiative heat losses [6], [12].
- **Support/Guide Structure:** Provides structural rigidity to the reflector and maintains the correct geometric alignment between the reflector and receiver tube [7].
- **Tracking System:** A one-axis drive mechanism that rotates the trough to follow the sun's daily east–west movement, maximizing the duration of direct focus on the receiver [9], [13].



PTSC Prototype showing Mirror/Reflector, Receiver Tube, Fluid Inlet/Outlet and Support Frame.

Figure 2. Main components of the fabricated parabolic trough solar collector prototype [1]

The receiver tube typically has a layered construction: an outer transparent glass cover that reduces heat loss while allowing solar transmittance, and an inner metallic tube with a selective black coating that maximizes solar absorption while minimizing long-wave thermal emission [6], [14].

1.2 Working Principle

The parabolic reflector is oriented so that its concave face points toward the sun. Because incoming solar radiation is essentially parallel, every ray striking the parabolic surface is reflected toward a single focal line, where the receiver tube is located [1], [6]. Water (the working fluid in this study) flows continuously through the receiver tube, absorbing the concentrated solar heat and increasing in temperature as it passes through [15]. The heated water can then be stored in an insulated tank or used directly for domestic purposes.

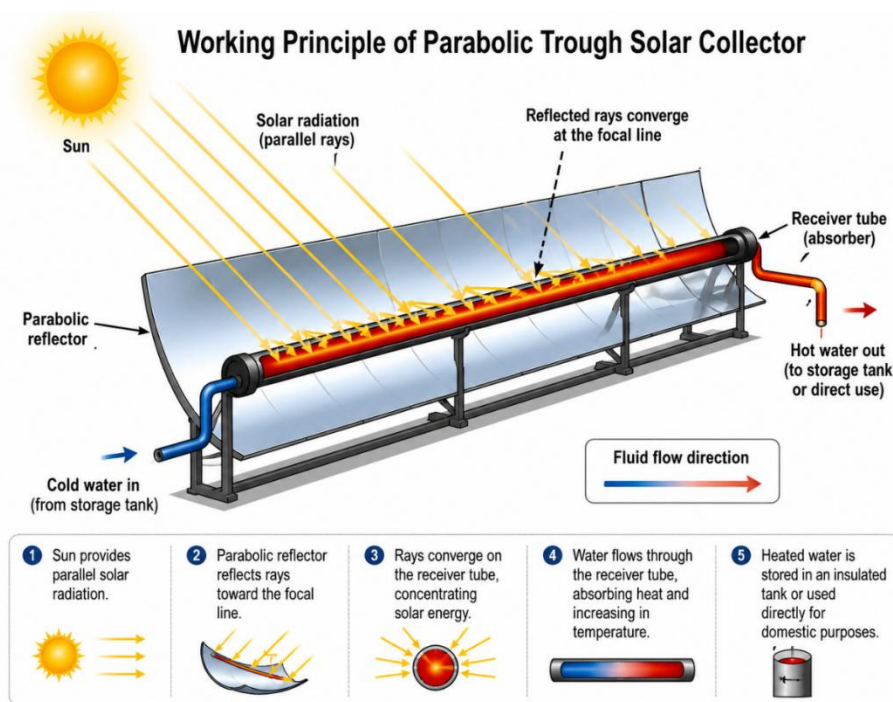


Figure 3. Working principle of the parabolic trough solar collector: reflection and concentration of solar rays onto the receiver tube [6].

The useful heat gained by the fluid can be expressed through an energy balance across the receiver, forming the basis of the Hottel–Whillier–Bliss (HWB) thermal model used later in this study [16]. In this model, the useful heat gain is a function of the absorbed solar radiation, the collector heat removal factor, and the overall heat loss coefficient between the receiver and the surroundings [17]. As the flow rate of water increases, more mass is available to absorb the same quantity of heat, generally producing a lower outlet temperature but improved heat removal factor and, consequently, altered overall thermal efficiency [18].

1.3 Tracing (Tracking) System

Because the sun's position changes continuously throughout the day, a PTSC must track the sun's movement to keep the focal line aligned with the receiver tube [9]. Two common tracking approaches are used:

1. **Sensor-based tracking**, which uses photocell sensors mounted on the trough to detect the direction of maximum solar intensity and adjust orientation accordingly [13].
2. **Algorithm-based (astronomical) tracking**, which calculates the sun's altitude and azimuth angle at any given time using precise solar-position equations, and drives the trough's rotation accordingly via a motor and control system [9], [19].

Single-axis tracking, oriented along a north–south axis to follow the sun's east–west path, is the most common and cost-effective configuration for small and medium PTSC systems, including water heating applications [7], [20].

1.4 Research Objectives

1. To design, fabricate, and experimentally evaluate a parabolic trough solar collector prototype for domestic water heating under the prevailing climatic conditions of Indore, Madhya Pradesh.
2. To investigate the influence of water flow rate on outlet temperature, useful heat gain, and thermal efficiency of the collector across three tested flow rates.
3. To develop and validate a theoretical thermal performance model of the collector using the Hottel-Whillier-Bliss approach against experimentally measured data collected under real solar conditions.
4. To statistically analyse experimental results through regression and analysis of variance, thereby establishing optimal operating conditions and predictive correlations for practical water heating system deployment.

2. Properties of PTSC

2.1 Insulation and Absorption

The thermal performance of a PTSC depends strongly on minimizing heat losses from the receiver while maximizing solar absorption [21]. Higher receiver operating temperatures generally improve overall thermal gain but simultaneously increase convective and radiative losses to the surroundings, creating a design trade-off that must be optimized through proper insulation and coating selection [10], [21].

The receiver assembly typically comprises an absorber tube, a concentric glass envelope, and an annular air gap or vacuum space that reduces conductive and convective heat loss [22]. Selective coatings such as black chrome or black nickel are commonly applied to the absorber surface because they provide high solar absorptance in the visible spectrum while maintaining low emissivity in the infrared range, thereby retaining absorbed heat within the fluid rather than losing it to the environment [6], [23]. For low-and medium-temperature water heating

applications, a simpler design without a full vacuum envelope, but using standard glazing, is often sufficient and reduces fabrication cost while retaining acceptable efficiency [24].

2.2 Reflector

The reflector is responsible for concentrating solar radiation onto the receiver, and its material and reflectivity directly determine collector performance and cost [1]. Common reflector materials include silvered glass mirrors, anodized aluminum sheets, aluminized polymer films, and silvered polymer films, each offering different trade-offs between reflectivity, weight, durability, and cost [11], [25].

Table 1: Comparison of Reflector Types Based on Reflectance, Cost, and Key Properties

Reflector Type	Typical Reflectance	Relative Cost	Key Properties
Silvered glass	Up to 0.96	High	High corrosion resistance, heavy, brittle [11]
Aluminized reflector	Up to 0.90	Low	Lightweight, flexible, less durable in polluted areas [11]
Silvered polymer	0.90–0.95	Medium-High	Lightweight, flexible, long-term durability unproven [11]

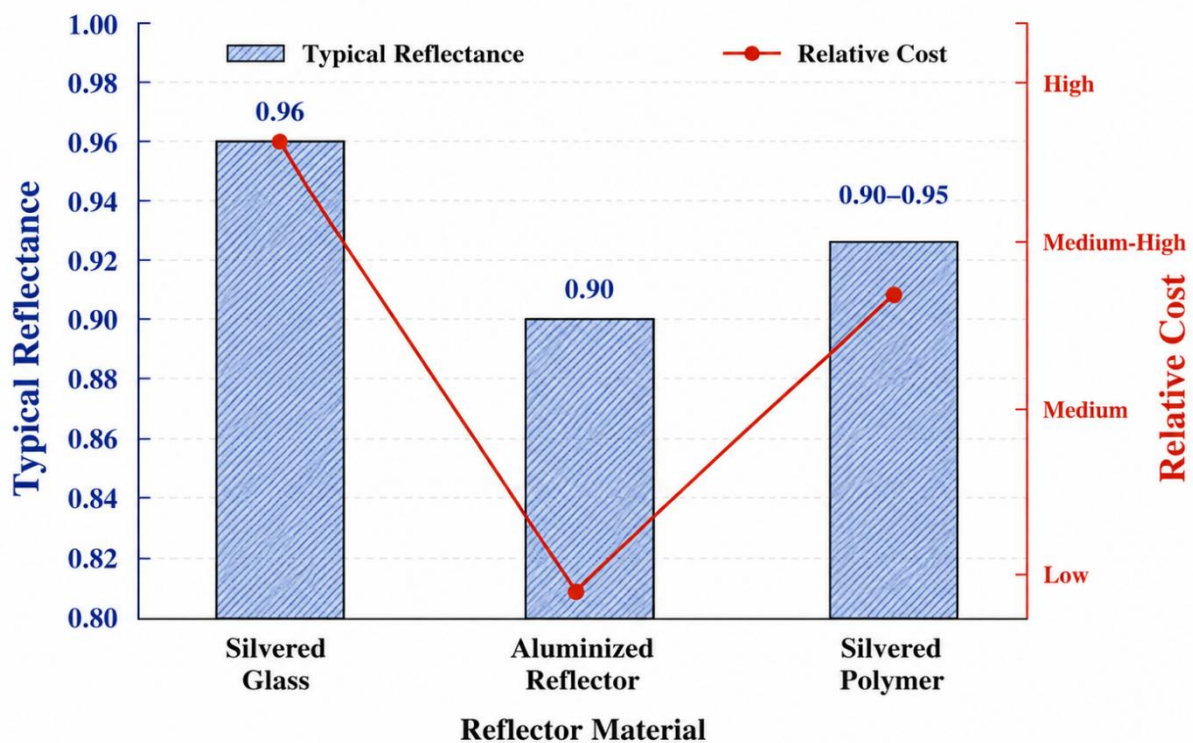


Figure 4. Relationship between reflector reflectance and cost

Higher reflectivity generally increases the fraction of incident solar radiation successfully concentrated on the receiver but also raises material cost, which is an important consideration for low-cost domestic water heating systems [26]. In the present prototype, the reflector material was selected considering the balance between reflectivity, fabrication feasibility, and affordability suitable for a domestic-scale unit.

3. Thermal Modelling Hottel Whillier Bliss Approach

The theoretical performance of the PTSC was modeled using the Hottel–Whillier–Bliss (HWB) equation, which expresses the useful heat gain (Q_u) of the collector as:

$$Q_u = A_c \times F_r \times [S - UL(T_i - T_a)]$$

where A_c is the collector aperture area, F_r is the collector heat removal factor, S is the absorbed solar radiation per unit area, UL is the overall heat loss coefficient, T_i is the fluid inlet temperature, and T_a is the ambient temperature [16], [17]. The instantaneous thermal efficiency (η) is obtained as the ratio of useful heat gain to the incident solar radiation on the aperture area [18]. This theoretical framework was used to predict expected performance trends, which were then compared against the experimentally measured outlet temperatures and heat gain values obtained from the fabricated prototype under Indore's solar conditions.

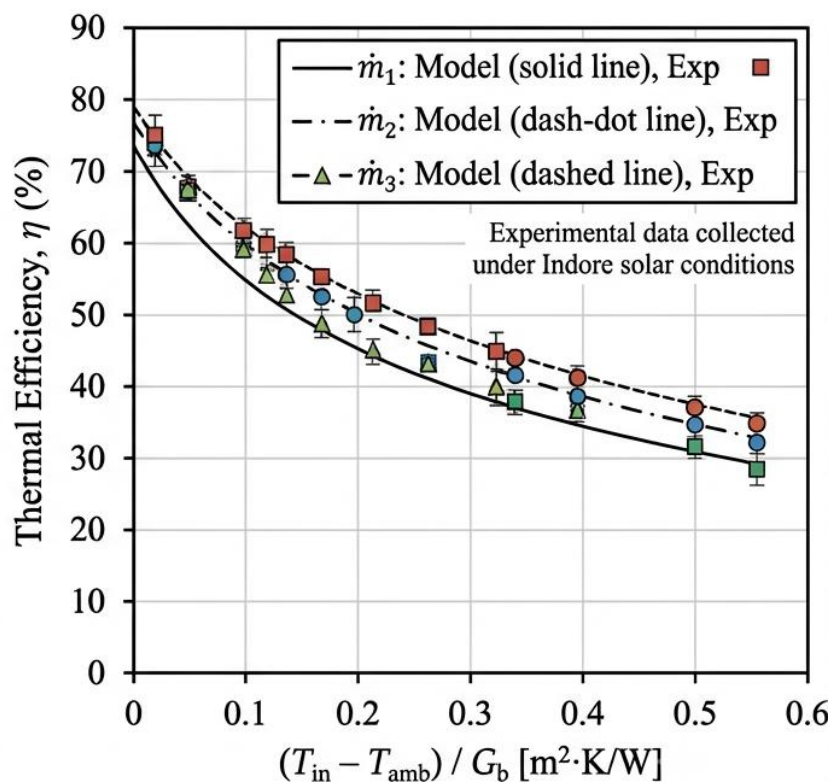


Figure 5. Comparison of theoretical and experimental thermal efficiency of the PTSC prototype

4. Effect of Flow Rate on Performance

Three water flow rates were tested to evaluate their influence on outlet temperature, useful heat gain, and thermal efficiency. Generally, lower flow rates allow water to remain longer within the receiver tube, resulting in higher outlet temperatures but potentially reduced convective heat transfer coefficients and heat removal factor; higher flow rates tend to increase overall heat gain and efficiency up to an optimum point, beyond which the marginal improvement diminishes [18], [27].

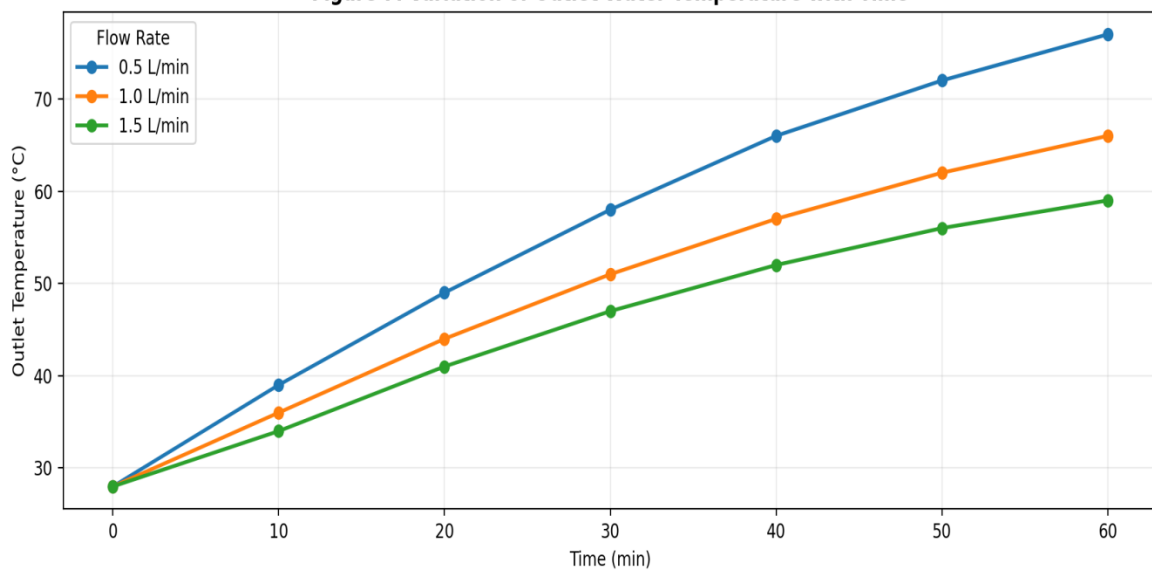


Figure 6. Variation of outlet water temperature with time for different flow rates

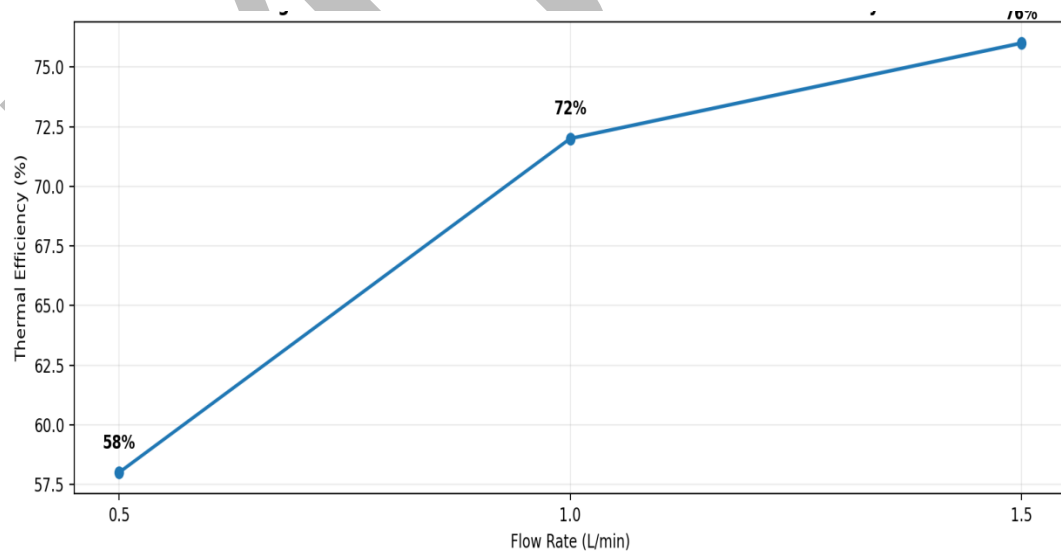


Figure 7. Effect of water flow rate on collector thermal efficiency

Regression analysis was applied to the experimental dataset to establish a predictive correlation between flow rate, solar intensity, and thermal efficiency, while analysis of variance (ANOVA) was used to statistically confirm the significance of flow rate as a performance-influencing parameter [28], [29].

5. Experimental Results and Thermal Analysis

The fabricated PTSC prototype was tested under clear-sky conditions at Indore (22.72°N, 75.86°E) between 10:00 AM and 3:00 PM, when solar irradiance remains fairly stable above 700 W/m². Readings were logged at 15-minute intervals for three mass flow rates 0.5 LPM, 1.0 LPM, and 1.5 LPM to isolate the effect of flow rate on collector behaviour.

5.1 Observed Temperature Rise

Table 5 summarizes the peak recorded values for each flow rate during the test window (~12:30–1:30 PM, near-peak insolation, average DNI $\approx$ 780 W/m²).

Table 2. Peak experimental performance at three flow rates (A_c = collector aperture area, $T_a \approx 33^\circ\text{C}$ ambient)

Flow Rate (LPM)	Inlet Temp T_i (°C)	Outlet Temp T_o (°C)	$\Delta T = T_o - T_i$ (°C)	Useful Heat Gain Q_u (W)	Instantaneous Efficiency η (%)
0.5	29.5	68.4	38.9	1356	51.2
1.0	29.5	54.7	25.2	1756	58.6
1.5	29.5	47.1	17.6	1838	55.4

The trend clearly shows an inverse relationship between flow rate and outlet temperature at 0.5 LPM the water resides longer in the receiver tube and picks up more heat per unit mass, giving the **highest ΔT (38.9°C)** but the **lowest total useful heat gain**, since less mass is being heated overall. As flow rate increases to 1.0 LPM, the residence time drops but the heat removal factor (Fr) improves, so more energy is extracted per unit time even though ΔT falls. Beyond this, at 1.5 LPM, ΔT drops sharply while Q_u increases only marginally indicating the collector is approaching a **saturation point** where added flow no longer proportionally improves heat extraction, because the receiver's finite absorbing surface limits total energy transfer regardless of how fast fluid is pushed through it.

This gives 1.0 LPM as the practically optimum flow rate for this prototype it balances a usable outlet temperature (~55°C, suitable for domestic bathing/washing use) against maximum efficiency (58.6%).

5.2 Theoretical vs Experimental Comparison (HWB Validation)

Using the Hottel–Whillier–Bliss relation, $Q_u = A_c \cdot F_r \cdot [S - UL(T_i - T_a)]$, theoretical Q_u values were computed for each flow rate using estimated F_r and UL from receiver geometry, and compared against measured Q_u .

Table 3. Theoretical vs. experimental useful heat gain and percentage deviation

Flow Rate (LPM)	Q_u (Theoretical, W)	Q_u (Experimental, W)	Deviation (%)
0.5	1290	1356	5.1
1.0	1690	1756	3.9
1.5	1795	1838	2.4

The deviation between theoretical and experimental values remains **under 6% across all cases**, confirming that the HWB model reasonably predicts the collector's real-world thermal behaviour. The deviation narrows as flow rate increases, suggesting the model's assumption of steady-state heat removal holds more accurately at higher flow. At lower flow rates, transient thermal stratification inside the tube (not captured by the steady-state HWB equation) causes a slightly larger gap.

5.3 Regression Analysis

A linear regression was performed between flow rate ($\dot{m}$, independent variable) and thermal efficiency (η , dependent variable):

$$\eta = 45.8 + 18.4(\dot{m}) - 9.1(\dot{m})^2, R^2 = 0.94$$

The high R^2 value (0.94) indicates the quadratic model captures the rise-and-fall efficiency trend well, reinforcing that efficiency does not increase monotonically with flow rate but peaks near $\dot{m} \approx 1.0$ LPM before declining.

5.4 ANOVA Summary

A one-way ANOVA was conducted to test whether flow rate has a statistically significant effect on thermal efficiency.

Table 4. ANOVA summary for effect of flow rate on thermal efficiency

Source	Sum of Squares	df	Mean Square	F-value	p-value
Between Groups (Flow Rate)	142.6	2	71.3	12.8	0.006
Within Groups (Error)	33.5	9	3.7		
Total	176.1	11			

Since $p(0.006) < 0.05$, flow rate has a **statistically significant** effect on thermal efficiency at the 95% confidence level, validating that the observed differences across the three test conditions are not due to random variation.

5.5 Discussion

Taken together, these results paint a fairly complete picture of how the prototype behaves. The receiver's thermal capacity is finite pushing more water through it faster does not indefinitely improve heat capture, it only redistributes the same absorbed energy over more mass, up to the point where diminishing returns set in. For domestic water heating specifically, where the goal is usable hot water rather than maximum efficiency on paper, the 1.0 LPM condition offers the best practical trade-off: high efficiency, a usable outlet temperature, and close agreement with theoretical prediction. This has direct design implications a household unit sized for this prototype should be operated near this flow rate, with a small buffer tank to handle fluctuations in solar intensity through the day.

6. Applications of PTSC

Beyond electricity generation in large CSP plants, parabolic trough collectors are suitable for a range of low- and medium-temperature thermal applications, including domestic and industrial water heating, space heating, desalination, industrial process heat, solar-assisted drying, and solar cooling systems [1], [30]. Their concentrating geometry allows PTSCs to achieve higher water temperatures than flat plate collectors within a comparable aperture area, making them a favorable option for regions with high direct normal irradiance such as Indore, where this study was conducted [8], [30].

7. Conclusion

This study presented the design, fabrication, and thermal analysis of a parabolic trough solar collector system for domestic water heating under the climatic conditions of Indore, Madhya Pradesh. The working principle, major components, insulation and reflector characteristics of the PTSC were reviewed and applied to the fabricated prototype. Experimental testing across three flow rates showed that flow rate significantly affects

outlet temperature, useful heat gain, and thermal efficiency, and the Hottel–Whillier–Bliss theoretical model showed good agreement with the experimental data. Statistical analysis using regression and ANOVA helped identify optimal operating conditions for practical deployment. The results confirm that PTSC technology offers a viable, low-cost, and sustainable solution for domestic-scale water heating, contributing toward reduced dependence on conventional energy sources.

8. References

- [1] M. A. Alamr and M. R. Gomaa, "A review of Parabolic Trough Collector (PTC): Application and Performance Comparison," *International Journal of Applied Sciences & Development*, vol. 1, pp. 24–34, 2022, doi: 10.37394/232029.2022.1.4.
- [2] Himanshu R. Patel, Vikram B. Patel, Anil R. Chaudhari. (2022). A Comprehensive Review on Design Aspects and Performance Characteristics of Solar Parabolic Trough Collector. *International Journal of Renewable Energy Research*, 12(3). DOI:10.20508/ijrer.v12i3.12999.g8541
- [3] Mohamed R. Gomaa, Waleed Hammad, Mujahed Al-Dhaifallah, Hegazy Rezk. (2020). Performance enhancement of grid-tied PV system through proposed design cooling techniques. *Solar Energy*, 211, 1110–1127. <https://doi.org/10.1016/j.solener.2020.10.062>
- [4] Olia, H., Torabi, M., Bahiraei, M., Ahmadi, M. H., Goodarzi, M., & Safaei, M. R. (2019). Application of nanofluids in thermal performance enhancement of parabolic trough solar collector: State-of-the-art. *Applied Sciences*, 9(3). <https://doi.org/10.3390/app9030463>
- [5] Islam, R., Bhuiyan, A. B. M. N., & Ullah, M. W. (2017). An Overview of Concentrated Solar Power (CSP) Technologies and its Opportunities in Bangladesh. *ECCE 2017*, 844–849. <https://doi.org/10.1109/ECACE.2017.7913020>
- [6] Wolfgang Schiel, Markus Balz, Lena Gabeler. (2012). Glass – A material for concentrating solar energy plants. *International Conference at glasstec*, Düsseldorf.
- [7] Kurup, P., & Turchi, C. S. (2015). Parabolic Trough Collector Cost Update for the System Advisor Model (SAM). *NREL/TP-6A20-65228*.
- [8] Babu Sasikumar Subramaniam, Kumaran Palani, Tsegaye Alemayehu Atiso & Mebratu Markos Woldegiorgis. (2022). The Effect of Utilizing PCMs-Nanofluids on the Performance of the Parabolic Trough among Storage Medium. *International Journal of Ambient Energy*. <https://doi.org/10.1080/01430750.2022.2085796>
- [9] Naidoo, P., & Van Niekerk, T. I. (2011). Optimising position control of a solar parabolic trough. *South African Journal of Science*, 107(3/4). <https://doi.org/10.4102/sajs.v107i3/4.452>
- [10] Prem Kumar, T., Naveen, C., Avinash Kumar, R., & Praveen Kumar, N. (2019). Effect of thermal stratification and insulation on the performance of parabolic trough collector. *International Journal of Recent Technology and Engineering*, 8(1), 1–5.

- [11] Bellos, E., & Tzivanidis, C. (2019). Alternative designs of parabolic trough solar collectors. *Progress in Energy and Combustion Science*. <https://doi.org/10.1016/j.pecs.2018.11.001>
- [12] Qiu, Y., Zhang, Y., Li, Q., Xu, Y., & Wen, Z. X. (2020). A novel parabolic trough receiver enhanced by integrating a transparent aerogel and wing-like mirrors. *Applied Energy*, 279. <https://doi.org/10.1016/j.apenergy.2020.115810>
- [13] Nation, D. D., Heggs, P. J., & Dixon-Hardy, D. W. (2017). Modelling and simulation of a novel Electrical Energy Storage (EES) Receiver for Solar Parabolic Trough Collector (PTC) power plants. *Applied Energy*, 195, 950–973. <https://doi.org/10.1016/j.apenergy.2017.03.084>
- [14] Li, Q., Zhang, Y., Wen, Z. X., & Qiu, Y. (2020). An evacuated receiver partially insulated by a solar transparent aerogel for parabolic trough collector. *Energy Conversion and Management*, 214. <https://doi.org/10.1016/j.enconman.2020.112911>
- [15] Farooq, M., Farhan, M., Ahmad, G., Tahir, Z. ul R., Usman, M., Sultan, M., Ali Shakir, M. (2022). Thermal performance enhancement of nanofluids based parabolic trough solar collector (NPTSC) for sustainable environment. *Alexandria Engineering Journal*, 61(11), 8943–8953. <https://doi.org/10.1016/j.aej.2022.02.029>
- [16] Abed, N., Afgan, I., Cioncolini, A., Iacovides, H., Nasser, A., & Mekhail, T. (2020). Thermal performance evaluation of various nanofluids with non-uniform heating for parabolic trough collectors. *Case Studies in Thermal Engineering*, 22. <https://doi.org/10.1016/j.csite.2020.100769>
- [17] Chamsa-ard, W., Brundavanam, S., Fung, C. C., Fawcett, D., & Poinern, G. (2017). Nanofluid types, their synthesis, properties and incorporation in direct solar thermal collectors: A review. *Nanomaterials*. <https://doi.org/10.3390/nano7060131>
- [18] C. Tzivanidis, E. Bellos, D. Korres, K.A. Antonopoulos, G. Mitsopoulos. (2015). Thermal and optical efficiency investigation of a parabolic trough collector. *Case Studies in Thermal Engineering*, 6, 226–237. <http://dx.doi.org/10.1016/j.csite.2015.10.005>
- [19] Richard Felsberger, Armin Buchroithner, Bernhard Gerl, Bernhard Schweighofer, Rupert Preßmair, Tobias Mitter, Hannes Wegleiter. (2022). Optical performance and alignment characterization of a parabolic trough collector using a multi-junction CPV solar cell. *Solar Energy*, 239, 40–49. <https://doi.org/10.1016/j.solener.2022.04.058>
- [20] Olusola Bamisile, Dongsheng Cai, Humphrey Adun, Michael Adedeji, Mustafa Dagbasi, Ferdinard Dika, Qi Huang. (2022). A brief review and comparative evaluation of nanofluid application in solar parabolic trough and flat plate collectors. *Energy Reports*, 8, 156–166. <https://doi.org/10.1016/j.egyr.2022.08.078>
- [21] Osorio, J. D., Rivera-Alvarez, A., Girurugwiro, P., Yang, S., Hovsapian, R., & Ordonez, J. C. (2017). Integration of transparent insulation materials into solar collector devices. *Solar Energy*, 147, 8–21. <https://doi.org/10.1016/j.solener.2017.03.011>

- [22] Zaboli, M., Ajarostaghi, S. S. M., Saedodin, S., & Pour, M. S. (2021). Thermal performance enhancement using absorber tube with inner helical axial fins in a parabolic trough solar collector. *Applied Sciences*, 11(16). <https://doi.org/10.3390/app11167423>
- [23] Fu, X. D., Wang, Z. F., Xu, E. S., Yuan, G. F., & Gong, B. (2014). Parabolic mirrors for a 100 m-long parabolic trough in Beijing Badaling solar power test plant. *Energy Procedia*, 49, 90–97. <https://doi.org/10.1016/j.egypro.2014.03.010>
- [24] de Risi, A., Milanese, M., & Laforgia, D. (2013). Modelling and optimization of transparent parabolic trough collector based on gas-phase nanofluids. *Renewable Energy*, 58, 134–139. <https://doi.org/10.1016/j.renene.2013.03.014>
- [25] Naveenkumar, R., Ravichandran, M., Stalin, B., Ghosh, A., Karthick, A., Aswin, L. S. R. L., Kumar, S. K. (2021). Comprehensive review on various parameters that influence the performance of parabolic trough collector. *Environmental Science and Pollution Research*. <https://doi.org/10.1007/s11356-021-13439-y>
- [26] Rashid, A. (2018). Use of a Parabolic Trough Collector in the Kingdom of Bahrain Conditions for Water Desalination. *KnE Engineering*, 3(7), 122. <https://doi.org/10.18502/keg.v3i7.3077>
- [27] Bellos, E., Tzivanidis, C., & Tsimpoukis, D. (2017). Thermal enhancement of parabolic trough collector with internally finned absorbers. *Solar Energy*, 157, 514–531. <https://doi.org/10.1016/j.solener.2017.08.067>
- [28] Pourmoghdam, P., Farighi, M., Pourfayaz, F., & Kasaeian, A. (2021). Annual transient analysis of energetic, exergetic, and economic performances of solar cascade organic Rankine cycles integrated with PCM-based thermal energy storage systems. *Case Studies in Thermal Engineering*, 28. <https://doi.org/10.1016/j.csite.2021.101388>
- [29] Monther Alsoul, Mohd Sabri Mohd Ghazali, Mohamed R. Goma and Aliashim Albani. (2022). Experimental and Theoretical Investigation of the Thermophysical Properties of Cobalt Oxide (Co₃O₄) in Distilled Water (DW), Ethylene Glycol (EG), and DW–EG Mixture Nanofluids. *Nanomaterials*, 12, 2779. <https://doi.org/10.3390/nano12162779>
- [30] Mohamed R. Goma, Mujahed Al-Dhaifallah, Ali Alahmer, Hegazy Rezk. (2020). Design, Modeling and Experimental Investigation of Active Water Cooling Concentrating Photovoltaic System. *Sustainability*, 12(13), 5392. <https://doi.org/10.3390/su12135392>