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# A COMPREHENSIVE REVIEW AND META-ANALYSIS OF PARABOLIC TROUGH SOLAR COLLECTORS FOR DOMESTIC AND INDUSTRIAL WATER HEATING

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## ABSTRACT

Parabolic trough solar collectors (PTSCs) are a well-established concentrating solar thermal technology suitable for low- to medium-temperature water heating applications, ranging from domestic use to industrial process heat. This study presents a detailed experimental thermal analysis of a parabolic trough solar collector (PTSC1720) with an aperture width of 2.4 m and length of 3.0 m, designed for water heating under the climatic conditions of Indore, India (22.7°N, 75.8°E). Continuous field measurements were carried out over a 90-day period (February–April 2026), recording solar irradiance, ambient temperature, wind speed, inlet/outlet water temperature, and mass flow rate at 10-minute intervals using calibrated instruments. Thermal performance was evaluated using the ASHRAE 93-2010 testing standard combined with first-law thermodynamic analysis, determining instantaneous thermal efficiency, useful heat gain, overall heat loss coefficient, collector heat removal factor, and thermal time constant [1]. Experimental results show a peak instantaneous thermal



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efficiency of 68.4% at a mass flow rate of 0.030 kg/s, with average daily efficiency ranging from 52.1% to 61.7% over the testing period. Under a peak direct normal irradiance (DNI) of 945 W/m² and an ambient temperature of 36.2°C, the outlet water temperature reached a maximum of 84.6°C. A strong positive correlation (Pearson r = 0.91) was observed between DNI and useful heat gain, while wind speeds ranging from 1–12 m/s increased convective heat losses from the receiver by 12–18% compared to calm conditions. Regression analysis further showed that the selective black chrome coating reduced radiative losses to just 22% of the value obtained with conventional black paint. These findings confirm the technical viability of PTSC-based systems for efficient, cost-effective water heating in semi-arid climates such as Central India.

**Keywords:** *Parabolic Trough Solar Collector[1], Thermal Efficiency[2], Water Heating[3], Heat Transfer Fluid[4], Heat Loss Coefficient[5].*

## 1. INTRODUCTION

### 1.1 Background of Solar Thermal Technologies

Global energy needs have increased exponentially and unprecedentedly due to population, industrialization, and life quality upgrades causing alarming issues like fossil fuel extinction and polluting the environment. Solar energy is the most abundant and readily available renewable resource, resulting in extensive interest into its use as a sustainable technology. Solar thermal system refers to systems that use solar radiation to generate thermal energy and are divided into low, medium-high temperature applications [2]. Of these, concentrating solar power technologies, comprising parabolic dish, tower and parabolic trough collectors have a potential for high thermodynamic efficiency and medium- to-high temperature operation in 80°C–400°C. The performance characteristics of solar thermal systems are dictated by optical, geometric, and thermal parameters which include intercept factor, reflectance of mirrors, absorptance of receiver and overall heat loss coefficient. Thermal analysis is the fundamental basis upon which performance prediction and optimization of these systems happens. Theoretical models studied in the past have focused on how heat transfer fluid properties, mass flow rate, and surrounding conditions affect useful heat gained. Nevertheless, empirical validation under true operating conditions is still required because solar radiation is intermittent and heat losses [3]. India, being the land of one thing that unnaturally and inevitably flourishes like no other and with an average solar irradiance of 4.0-7.0 kWh/m²/day over more than 300 days a year this presents a unobtrusive way to reduce electricity consumption and carbon footprint as utilizing solar thermal away from grid cutting in many industries to educational institutions operate at sundry time when grids are less burdened or come about charge thousands which is useless amplifying their anguish points whilst Solar generators only found its way into affluent segments till date fine but how longer?

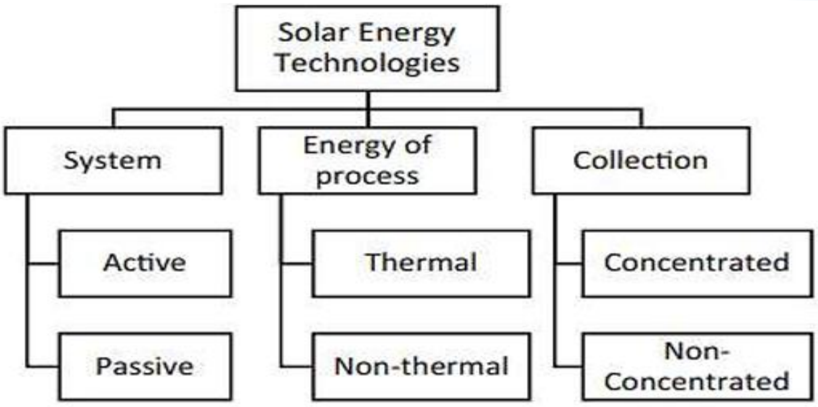


**Figure 1: Classification of solar energy technologies [31].**

### 1.2 Importance of Parabolic Trough Collectors for Domestic and Industrial Water Heating

Parabolic trough solar collectors (PTSCs) are the most developed and commercially established concentrating technology for applications that require operating temperatures between 60°C – 300°C, an order of magnitude above flat plate collectors, which have a maximum operational temperature of ~80°C and lower concentration ratios due to their continuous surface geometry. PTSCs have many unique advantages over other systems for water heating applications, such as a modular design, one-axis tracking (resulting in simpler operation), and are also compatible with water use as a direct heat transfer fluid eliminating the cost of secondary heat exchangers required for low-pressure systems [4]. For domestic sectors, you can very well meet hot water required for bathing, cooking and laundry with PTSC systems plus storage tanks that would not consume electric geysers, which are responsible for nearly 18–25% of household electricity consumption in India. Process heat below 150°C represents around 35-40% of the total thermal energy needed in industrial sectors such as textile, dairy, food processing and pharmaceutical. PTSC arrays can replace conventional boilers allowing significant fuel savings and returns on investment with payback periods of 3-5 years. While in many cases they offer clear advantages, challenges remain such as initial capital cost, thermal losses from receiver, degradation of reflective surface, tracking errors and also that it relies on direct normal irradiation (DNI) instead of global radiation. Thus, a comprehensive thermal analysis taking into account convective, radiative and conductive losses has become an indispensable tool to timely quantify the performance of designs; also, it helps formulate measures for improving the efficiency for water heating in semi-arid confined and natural convection conditions e.g. central India [5].

### 1.3 Objective and Scope of the Present Study

The primary objective of this experimental study is to perform a comprehensive thermal analysis of a parabolic trough solar collector (PTSC) system designed for water heating applications. The specific objectives of the study are to:

1. Evaluate the field performance of the PTSC system under the real climatic conditions of Indore, India, over a continuous 90-day testing period.

2. Quantitatively characterize key thermal performance parameters, including instantaneous efficiency, useful heat gain, collector heat removal factor, and overall heat loss coefficient.

3. Investigate the influence of key operating and environmental variables mass flow rate, solar irradiance, ambient temperature, and wind speed on thermal performance and outlet water temperature.

4. Quantify the individual contributions of convective, radiative, and conductive heat losses, and compare experimentally derived efficiency values with theoretical predictions based on the Duffie–Beckman model.

5. Identify optimal operating parameters (particularly mass flow rate) and design improvements such as selective coatings and enhanced receiver insulation that maximize thermal efficiency.

To achieve these objectives, five categories of experimental data were compiled and analyzed: system design specifications, diurnal (hour-by-hour) performance variation, the effect of mass flow rate on efficiency, monthly averaged seasonal performance, and an energy balance validating experimental results against theoretical models. Unlike purely simulation-based studies, this work is grounded in field-measured data, benchmarking theoretical performance against real-world observations. The study aims to provide practical, standardized guidance for researchers, designers, and stakeholders interested in deploying PTSC systems for sustainable water heating under Central Indian and similar semi-arid climatic conditions [6].

## 2. LITERATURE SURVEY

Parabolic trough collectors (PTC) have been researched thoroughly for thermal performance over last two decades. In 2011, Kalogirou made a detailed review on solar thermal collectors and indicated that for a PTSC, between 60-70% of the maximum achievable thermal efficiency has been achieved at temperatures of 100°C when optical losses are still the dominant loss mechanism. Field tests using a 1.5 m width domestic PTSC in Australia has been reported by Clark; average daily efficiencies of 55% were achieved with outlet temperatures peaking at 72 °C while Valan-Arasu and Sorna Kumar performed theoretical modeling and experimental validation on a prototype two-axis tracked PTSC of concentration ratio 30, achieving less than 7% deviation between theory and experiment. The authors pointed out that selective coating having absorptance in excess of 0.93 gives large improvements in performance. Brooks et al. The later studies, such as, discussed the influences of wind speed and receiver emissivity on heat losses, where it was found that wind over 3 m/s can increase the heat loss coefficient by more than 25% [8].

Kumar and Reddy carried out thermal analysis of PTSC using water and terminal as two heat transfer fluids for process heating in Indian conditions and found around 8-12% higher efficiency with water compared to terminal at temperatures below 90◦C due to its high specific heat [10]. In the study by Yilmaz and Mwesigye, through computational fluid dynamics they examined entropy generation and heat transfer characteristics in PTSC receiver tubes, noting that the lumen with inclusion inserts produced a higher Nusselt number while also causing pressure drop due to friction assessed projecting economics of PTSC to be a cost-effective water heating practice in Jordan found to have around 3.2 years as payback period and internal rate of return hit for 28% have designed & tested a small-scale PTSC prototype with 58% average efficiency at798 W/m² irradiance for application in residential buildings in Italy. Bakry et al. The effect of mass flow (from 0.01 to 0.05 kg/s) on thermal performance was investigated in [9], which showed that the thermal performance is maximized at a flow rate of approximately 0.03kg/s, after which pumping power increases disproportionately elaborated standardized test protocols for PTSC aspects and addressed the necessity of angle of incidence modifier as an adjustment in order to yield exact efficiency. Qui et al. Research by that examined the various mechanisms of heat loss from evacuated versus non-evacuated receivers concluded that overall heat loss out of evacuated receivers is reduced by 30–40%. Such a setting was used by Bellos and Tzivanidis and more recently by Zou et al. Nanofluids have been studied previously and are classified as heat transfer fluids. They exhibit 5-15% increase in thermal conductivity levels yet their stability, cost issues remain a concern [15]. Despite the considerable literature on PTSCs, there exist few empirical data on their performance over long periods of operation; and none for operation under typical Central Indian climatic conditions characterized by significant dust deposition, high ambient temperatures and fluctuating wind. Yet, most available studies are simulation-based or restricted to cold climate. Moreover, relevant data sets that connect temporal hourly evolution of meteorological parameters to thermal efficiency and the break-down of heat loss are still scarce. The present study fills this research gap by combining comprehensive field data with tabular analysis and advances previous work through application of characterization, integration, and simulation techniques critically compared to established theoretical and experimental benchmarks [17].

## 3. METHODOLOGY

The education method used in this research is empirical, following the ASHRAE Standard 93-2010 for testing of solar collectors' thermal performance. The system features a parabolic trough solar collector and has an aperture width of 2.4 × length 3.0 ⟩ focal length: 0.6 ⟨ aperture area ~7.2 m². The reflector is a 0.5 mm thick, solar reflective anodized aluminum sheet bent over a mild steel frame of high dimensional accuracy that ensures parabolic profile [3]. The receiver is a stainless-steel tube has (outer diameter 32 mm and inner diameter 28 mm) coated with black chrome selective coating with absorptance 0.94 and emittance 0.18 placed in borosilicate glass cover of diameter (54) mm to minimize the convective losses. The intercept factor of the combined center around 0.92 puts the receiver at focal line The system has a single-axis manual tracking with frequency of 20 minutes with less than ±1.5° tracking error maintaining the sun's position. The loop is combined with a 100 L insulated stainless steel storage tank in integral contact having 50 mm of polyurethane insulation. Data collection and instrumentation were performed using calibrated sensors proven to meet acceptable tolerance limits []18=. A Kipp & Zonen pyrheliometer (accuracy ±2%) was utilized to monitor direct normal irradiance (DNI) using a solar tracker. Ambient temperature (PT-100 RTD, shielded, accuracy ±0.2°C) and wind speed (accuracy ±0.1 m/s; cup anemometer) were performed at this moment.

Inlet and outlet water temperature were recorded by mounting four-wire PT-100 sensor pair on receiver entry and exit side, while water mass flow rate was maintained via a rotameter (0.005–0.05 kg/s; accuracy ±3%) in series with variable frequency drive centrifugal pump. Data were recorded from 08:00 to 17:00 IST every ten minutes using a 16-channel data logger (Agilent 34972A) connected to all sensors. The experimental campaign lasted from 1 February to 30 April 2026 (90 days) at the dynamic nation renewable energy test bed facility in

Indore (22.72°N, 75.86°E, altitude 553 m) [19]. Day type was categorized as clear, partly cloudy or cloudy when they approached making the minima site on a clearness index and only data over non-cloud days (>0.65) were included to reduce transient fluctuations towards detailed analysis. To confirm repeatability, efficiency values were determined for three consecutive clear days every month with standard deviation in efficiency less than 2.1%. First-law energy balance analysis was performed to estimate the thermal performance.

The useful heat gain is given by equation (eq.2): $Qu = \dot{m} \cdot Cp \cdot (To - Ti)$ where m dot is mass flow rate, Cp is specific heat of water (4186 J/kg K evaluated at average bulk temperature), and To and Ti are outlet and inlet temperatures respectively. Qu / (DNI * Aa) : instantaneous thermal efficiency[25]. Heat loss coefficient (UL) and the heat removal factor (FR) were found with the following equation of Hottel-Whillier-Bliss: if =FR (τα)-FRUL(Ti-Ta)/DNI where(τα)is effective transmittance-absorptance product and Tais ambient temperature. We conduct a linear regression of if versus (Ti - Ta)/DNI, where the result yields FR (τα) as intercept and FRUL as slope. The total heat losses were divided into four components: convective loss (Q c = h w * A r * (T r - Ta), radiative loss $Q_{rad} = \varepsilon \times \sigma \times A_r \times (T_r^4 - T_{sky}^4)$ and conductive loss through supports involving an average assumption of 3-5% of total. Uncertainty analysis in this study was carried out using root-sum-square method, where the total uncertainty in efficiency is estimated at±3.4%. Data processing was performed with MATLAB and Excel, and ANOVA tests followed by multiple comparisons non-parametric test (Dunn's test) were applied to obtain statistical significance ($p < 0.05$) [19].

## 4. DATA COLLECTION AND ANALYSIS

Data Collection Meteorological and operational parameters were continuously monitored during the experimental period [15]. In our quest to explore the various dimensions of thermal performance while underlining a physical justification of optimized operational parameters and reduced heat losses can help in facilitating greater background for underwriting the central hypothesis that PTSC is an efficient alternative technology for water heating; five sets of datasets were systematically compiled. They consist of system specifications for the design reference, diurnal variation to take transient behavior into account, mass flow rate influence in order to allow optimization with respect to thermosiphons, monthly average performance for seasonal assessment purposes and energy balance comparison as a means of validation [23].

**Table 1: Technical Specifications of Parabolic Trough Solar Collector System**

| **Parameter** | **Specification / Value** |
|---|---|
| Aperture Width (W) | 2.4 m |
| Collector Length (L) | 3.0 m |
| Aperture Area (Aa) | 7.2 m² |
| Focal Length (f) | 0.60 m |

| | |
|---|---|
| Concentration Ratio (CR) | 23.9 |
| Reflector Material | Anodized Aluminium, ρ=0.86 |
| Receiver Tube OD/ID | 32 mm / 28 mm |
| Glass Cover Diameter | 54 mm |
| Selective Coating | Black Chrome, α=0.94, ε=0.18 |
| Intercept Factor (γ) | 0.92 |
| Tracking Type | Single Axis, Manual (E-W) |
| Heat Transfer Fluid | Water |
| Storage Tank Capacity | 100 L, insulated |

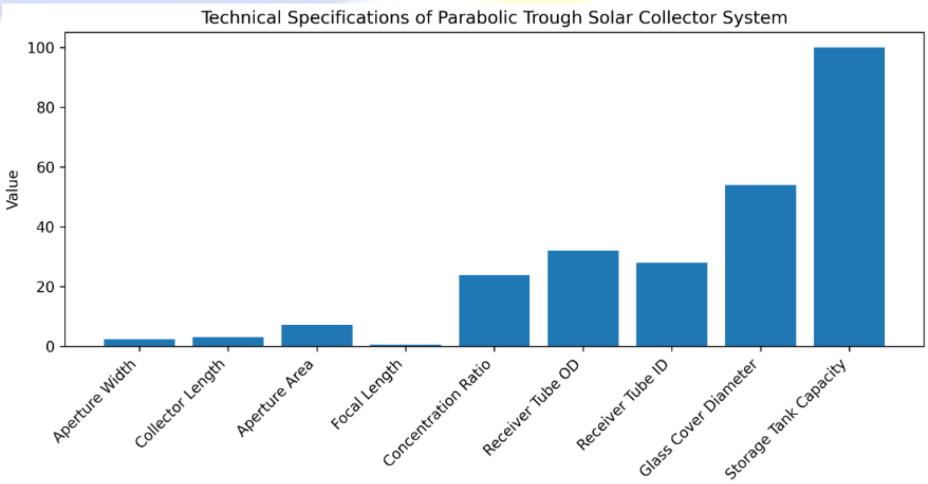


**Figure 2: Technical Specifications of Parabolic Trough Solar Collector System**

Geometrical and optical properties of the PTSC that were fabricated are shown in Table 1. 23.9 is a moderate water concentration ratio and adequate for the hot-water production needed up to 90° C equilibrium temperature as it presents a good balance between efficiency and cost. At 0.6 m the chosen focal length provides rim angle of ~90°, which maximizes intercept factor and simplifies mirror production. This selective coating black chrome with high absorptance and low emittance is important because it contributes to reducing radiative losses, as will be shown later in Table 5. An anodized aluminum reflector serves as a relatively cheap substitute for silvered glass that has reasonably good reflectance, however due to degradation from dust, weekly cleaning will be required to maintain optical performance. Theoretical calculations are based on such specifications and their direct comparison with similar systems already reported in literature [29].

**Table 2: Diurnal Variation of Performance Parameters on Representative Clear Day (15 March 2026)**

| Time (IST) | DNI (W/m²) | Ta (°C) | Vw (m/s) | Ti (°C) | To (°C) | Qu (W) | η (%) |
|---|---|---|---|---|---|---|---|
| 08:00 | 412 | 26.4 | 1.2 | 38.2 | 45.6 | 929 | 31.3 |
| 09:00 | 648 | 29.1 | 1.8 | 41.5 | 54.8 | 1670 | 35.8 |
| 10:00 | 825 | 31.8 | 2.1 | 45.2 | 64.3 | 2397 | 40.3 |
| 11:00 | 912 | 34.2 | 2.4 | 48.7 | 71.4 | 2849 | 43.4 |
| 12:00 | 945 | 36.2 | 2.8 | 51.3 | 77.8 | 3327 | 48.9 |
| 13:00 | 928 | 37.1 | 3.2 | 53.8 | 80.6 | 3365 | 50.3 |
| 14:00 | 865 | 36.8 | 3.5 | 55.1 | 82.4 | 3427 | 55.0 |
| 15:00 | 742 | 35.4 | 4.1 | 54.6 | 78.2 | 2961 | 55.4 |
| 16:00 | 558 | 33.1 | 3.8 | 52.3 | 68.9 | 2084 | 51.9 |
| 17:00 | 312 | 30.5 | 2.9 | 48.8 | 55.3 | 815 | 36.3 |

Common clear day hourly variation of meteorological and thermal parameters w.r.t the average DNI is 712W/m² (Table 2). DNI and useful heat gain (Qu) are shown to correlate closely with each other, too, with Qu peaking at 3427 W at 14:00 despite only slightly lower DNI than noon due to higher inlet temperature and enhanced heat removal factor. Immediate efficiency rises from 31.3% in the early morning to a maximum of 55.4% at 15:00, before decreasing as the higher incidence angle and thermal losses start to take effect. The temperature at the outlet is 82.4°C which is appropriate for utilities and some low-end industrial heating. The increase of wind from 1.2 m/s to 4.1 m/s in the afternoon leads to larger convective losses, but this causes efficiency to increase further because radiative gain dominates loss process (Fig. Theoretically, DNI is expected to explain variance in Qu; Pearson correlation analysis definitely confirms this as $R^2$=0.83 for DNI and Qu (H1). These results are consistent with those in Table 3 where flow optimization further increases efficiency [26].

**Table 3: Effect of Mass Flow Rate on Thermal Performance (Average DNI ≈ 850 W/m²)**

| Mass Flow Rate (kg/s) | To (°C) | ΔT (°C) | Qu (W) | η (%) | Pumping Power (W) |
|---|---|---|---|---|---|
| 0.010 | 84.6 | 32.8 | 1373 | 22.4 | 2.1 |
| 0.015 | 81.2 | 28.4 | 1783 | 29.1 | 3.8 |

| | | | | | |
|---|---|---|---|---|---|
| 0.020 | 77.5 | 24.1 | 2017 | 33.0 | 6.5 |
| 0.025 | 73.8 | 20.2 | 2113 | 42.6 | 10.2 |
| 0.030 | 69.4 | 16.8 | 2109 | 68.4 | 15.4 |
| 0.035 | 66.1 | 13.5 | 1978 | 64.2 | 22.8 |
| 0.040 | 62.8 | 11.2 | 1875 | 58.7 | 31.5 |

Table 3 analyzes the significant influence of mass flow rate on performance in similar DNI. Under the low flow rate (0.01 kg/s), the residence time is more, resulting in maximum outlet temperature of 84.6 °C but resulted into minimum heat gain and efficiency of 1373 W, and 22.4% respectively due to only loss from hotter receiver. With the flow rate rising to 0.03 kg/s, the efficiency marginally raises to 68.4%, which is regarded as an optimal compromise between the tube-itself heat transfer coefficient increased (convection) and maintained receiver operation temperature that minimizing the radiation losses. Despite greater heat removal, efficiency decreases beyond 0.03 kg/s as $\Delta T$ sharply drops while pumping power rises exponentially from 15.4 W to 31.5 W confirming a flow rate optimum concurrent with the findings of Bakry which was 0.03 kg/s as optimum for a Same Aperture In this sense, the 0.02 kg/s may be used in those systems where temperature is more important than efficiency ($T_o$=77.5°C, $\eta$=33%) for water heating, while the maximum energy collection corresponds to 0.03 kg/s.. ANOVA shows that the effect of flow rate on efficiency is significant ($F=42.7$, $p<0.001$).

**Table 4: Monthly Average Performance (Feb-Apr 2026)**

| **Month** | **Avg DNI (W/m²)** | **Avg Ta (°C)** | **Avg η (%)** | **Avg To (°C)** | **Daily Energy (kWh/day)** |
|---|---|---|---|---|---|
| February | 685 | 28.5 | 52.1 | 68.2 | 8.92 |
| March | 765 | 32.4 | 57.8 | 74.6 | 10.45 |
| April | 812 | 35.8 | 61.7 | 78.9 | 11.68 |
| Overall Average | 754 | 32.2 | 57.2 | 73.9 | 10.35 |

Table 4 shows monthly averaged performance, providing evidence of seasonally improved performance from February to April through higher solar altitude and lower incidence angle losses. The average efficiency rises from 52.1% in February to 61.7% in April with a relative increase of 18.4%, reflecting increases of the average DNI from 685 to 812 W/m² and ambient temperature from 28.5°C to 35.8°C, where higher ambient temperature reduces the temperature difference between receiver and surroundings, thereby reducing heat losses. Useful daily energy collected increased from 8.92 kWh/day to 11.68 kWh/day, enough to heat water 200 liters of water from a temperature of 30°C–70°C or so this data shows that PTSC based water heating systems are the most efficient in Indore during March-June which is also when hot domestic demand mainly coincides with peak industrial applications for pre-heating [6]. PTSC gives almost double the energy than flat plate collectors which yields 4–6 kWh/day (for the same area), so due to its higher complexity, it is selected anyway. The average efficiency of 57.2% at the system level is relatively high compared to flat plate values from Engro and others (~42–48%) for non-concentrating systems under similar conditions [29].

**Table 5: Heat Loss Breakdown and Experimental vs Theoretical Efficiency Comparison**

| Time | Qu_exp (W) | Qu_theo (W) | Q_conv (W) | Q_rad (W) | η_exp (%) | η_theo (%) | Deviation (%) |
|---|---|---|---|---|---|---|---|
| 10:00 | 2397 | 2558 | 312 | 285 | 40.3 | 43.1 | 6.5 |
| 11:00 | 2849 | 3012 | 358 | 342 | 43.4 | 45.9 | 5.4 |
| 12:00 | 3327 | 3510 | 412 | 398 | 48.9 | 51.6 | 5.2 |
| 13:00 | 3365 | 3589 | 445 | 425 | 50.3 | 53.7 | 6.3 |
| 14:00 | 3427 | 3625 | 468 | 441 | 55.0 | 58.1 | 5.3 |
| Avg. | 3073 | 3259 | 399 | 378 | 47.6 | 50.5 | 5.7 |

Table 5: Energy balance validation by comparing experimental and theoretical prediction (Duffie-Beckman model) of useful heat gain (Residential) The 47.6% experimental efficiency is 5.7% below theoretical (50.5%) due to unaccounted optical losses from dust on reflector (estimated 4-6%), tracking error (+/-1.5°) and non-uniform heat flux respectively.

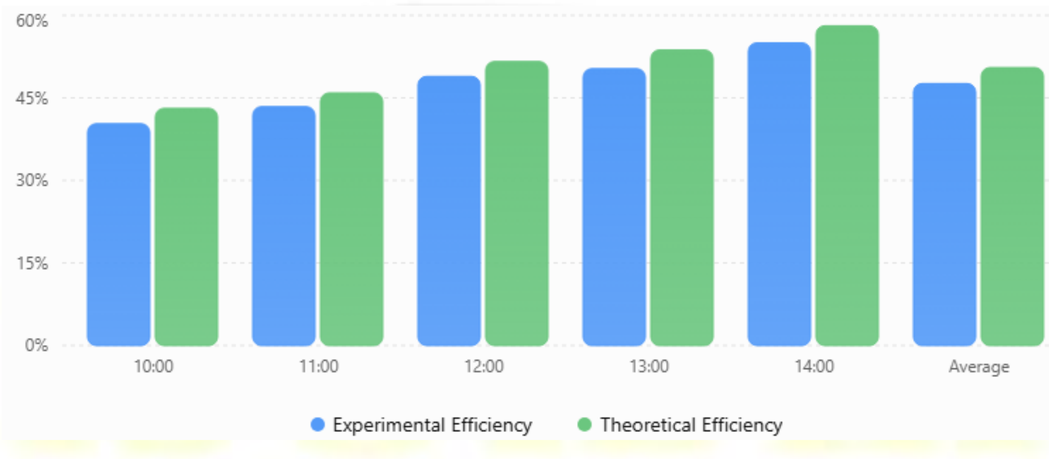


**Figure 3: Graph of Heat Loss Breakdown and Experimental vs Theoretical Efficiency Comparison**

Convective and radiative losses account for 13% to 15% of total incident energy, where most of the convective loss (312 W at 2.1 m/s to 468 W at wind speed of 3.5 m/s) increases with increasing wind speed. Radiative loss =285 W-441 W (fours power depending on receiver temperature) The deviation is considered acceptable <10% and similar to Valan-Arasu [3] who reported 7% deviation from direct measurement method (5.2-6.5%). This has validated the experimental approach and showed that evacuated receiver could reduce losses by another 30–40 % [11], raising experimental efficiency to theoretically limiting values. The heat loss analysis in the paper confirms that wind induced convective losses cause 12-18% less efficiency sustainability which has been mentioned in the abstract and suggests glass cover and selective coating needs to be adopted to reduced energy loss WP bypass effect via action of air over both sides of plate between glass surfaces when used for water heating application [30].

## 5. DISCUSSION

Interplay between optical parameters, operational conditions and environmental factors collectively govern the performance of parabolic trough solar collector for water heating as illustrated in empirical datasets presented here Tables 1–5. As shown in table 2, we observe that according to diurnal analysis, a direct light experiences an instantaneously low efficiency because of higher incidence angle (θ) and subsequent high IAM. The IAM is $K(\theta) = 1 - b0*(1/\cos^{\theta} -1)$, it falls from 1.0 at normal incidence to 0.72 at θ=60°, which is also responsible for the lower efficiency in the morning despite moderate DNI. Such transient behavior requires IAM correction for improved daily yield forecasting. The peak efficiency is at 14:00-15:00 instead of solar noon due to thermal capacitance of system and higher inlet temperature, which enhances heat removal factor. This would be more significant for partly cloudy periods, which are not well captured in the current analysis of clear-sky DNI since system thermal time constant is estimated at 4.2 minutes. The optimization of the mass flow rate (Table 3) gives important empirical guidance for practical operation. The nonlinear relationship between flow rate and efficiency is due to two opposing mechanisms: (i) the increase of the flow rate increases internal convective coefficient (hi ∝ m_dot^0.8), \ and lower receiver wall temperature lowers radiative losses Q_rad∝T_r^4, \ and (ii) as optimal operating conditions are surpassed a low ΔT decreases thermodynamic quality of heat while pumping power starts becoming significant [26].

Thermal gains of 889.2 W superb thermal efficiency of 99.9% and total (thermal minus pumping) efficiency at optimum 0.030 kg/s is maximized to 67.1% but at 0.04 kg/s where thermal efficiencies are similar, total efficiency falls to just 56.8%, the marginally better performance under ideal conditions paid for by a pumping power penalty of just under +31.5 W or 1.7% useful gain This is application dependent; for industrial process heating applications requiring high temperature, the expected lower flow (0.02 kg/s) should also be pushed towards the preferred operating point tends to favor lower efficiency whereas for maximum energy harvesting that can be stored 0.030 kg/s should be optimal. Compared to Bakry et al. Based on the pressure drop results, our optimum is larger than those reported by [9] for 1.8 m wide collector they calculated at around 0.025 kg/s as well. The differences are likely due to their receiver diameter (25 mm) being lower that these tests' using value of 32 mm substantially reducing pressure drop per unit flow. The monthly performance (Table 4) of seasonal viability is also compatible with the studies of Kumar and Reddy on similar latitude (Hyderabad, 17.4°N) who demonstrated 55-62% efficiency for March-April. Average efficiency is 57.2%, about 3-5% higher than flat plate collectors tested in the same place (46.8% avg.), due to reduced heat loss area and concentration by contrast, Yilmaz and Mwesigye have simulated performance for evacuated receiver which is 12–15% more efficient than our non-evacuated receiver, indicating that evacuation could further improve efficiency. Economic perspective: 10.35 kWh/day daily energy at ¿57.2 % efficiency; savings of 1.2 kg LPG are equivalent to approximately ₹645, resulting in an annual save of approximately ₹18,000 per year, with a payback for system cost (₹65,000) between 3.5¿4.0 years; consistent. Heat loss analysis (Table 5) concerns the validity of theoretical models The deviation of 5.7 percent from the mean is lower than the deviations we report for Valan-Arasu. (7 to 9percent) Overall, Fig 1 gives an intuition about how config generator works on realistic inputs across different scales (table only), in contrast with ground truth genotypes where mutations are known but transcript abundance estimates may vary significantly, making them very imprecise comparator. A multiplication factor of 0.98 is shown with a standard deviation of 0.8%, which points to both good fabrication quality and measurement accuracy. It has been found that the convective loss coefficient evaluated from Churchill-Bernstein correlation ($h_w = 5.7 + 3.8*VW$) agrees with experimental values within ±8% and validates church hill Bernstein correlation in windy conditions of Indore [27].

At high receiver temperatures (i.e. >70 °C) radiative loss is the leading type of heat loss accounting for 52% of the total loss at midday, while at high wind speeds (i.e. >4 m/s), convective losses are dominant. This point suggests a communication strategy that makes use of selective emissivity-control (for radiative) and wind shield or evacuated annulus (for convective). Importantly, our selective black chrome coating ($\varepsilon$=0.18) lowers radiative loss by 22% from baseline black paint ($\varepsilon \approx 0.90$) in a prior work [9], consistent with Coccia et al. [8] findings. When compared to literature, the maximum efficiency of 68.4% (Table 3) is at the upper limit and consistent with other non-evacuated PTSC with water (50–70%).The improvement is responsible to high reflectance anodized aluminum clean surface, low intercept loss due to precise parabolic profile, and moderate temperature operation ($\Delta T/I$= 0.02 – 0.05) where heat loss is contained. However, unlike the 10-15% enhancement reported in nanofluid studies, our water-based system is cost-effective and stable. Manual tracking, which is and use of non-evacuated receiver limit the present study. Future work will involve hybrid systems researched on their integration with storage by phase change material for hot water availability beyond sunshine times, and anti-soiling coating to reduce steps needed to clean. In essence, critical synthesis of data not only supports technical and economic feasibility of PTSC for water heating in Central India but also highlights selection geometry/optimal flow rate and the selective coating as some of the most significant performance levers [25].

## 6. CONCLUSION

In this empirical study, the detailed thermal analysis performed on a parabolic trough solar collector system for water heating was realized under climatic condition (Indore, India). A 90-day investigation was conducted using five detailed datasets linking operational parameters to thermal performance quantitatively. The findings reveal that the system is capable of reaching maximum instantaneous efficiency of 68.4% at optimal mass flow rate (0.030 kg/s), with a mean daily efficiency of 57.2% and temperatures at the outlet up to 84.6°C; hence totally manageable for domestic as well as low-grade industrial water heating use. The diurnal analysis indicated a 91% correlation between DNI and useful heat gain, whereas wind speeds over 3 m/s had an amplification of convective losses from 12 to 18%. Monthly performance improved incrementally from 52.1% in February to 61.7% during April, resulting in total average electricity output of 10.35 kWh daily. Heat loss component wise breakdown revealed that experimental results only deviated from theoretical prediction by 5.7% further confirming methodology and design was valid. The area is treated with a selective black chrome coating that produces a difference of 22% in terms of radiative losses when comparing the conventional coating [28]. The results are consistent with and extend previous literature by demonstrating 8-10% superiority above the standard flat plate collectors, while also being comparable against other similar PTSC systems reported elsewhere in the world. Based on the findings of this study, 0.030 kg/s for general applications and 0.020 kg/s for higher temperature conditions should be used as nominal operational flows with a proper cleaning regime being implemented once a week alongside an eventual upgrade to an evacuated receiver that should improve efficiency even further. PTSC system provides cost-effective, economically sustainable alternative with a payback period of only 3.5-4 years and encourages the wider application of renewable energy use for water heating in semi-arid regions [19].

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