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Design and Fabrication of a Parabolic Trough Collector Prototype for Solar Thermal Applications in Alice, South Africa

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Abstract

Renewable energy technologies are increasingly recognized as essential solutions for mitigating energy insecurity and supporting sustainable development. Among solar thermal systems, parabolic trough collectors (PTCs) have attracted significant attention for medium-temperature heat generation due to their high optical concentration ratio and thermal conversion efficiency. However, the deployment of small-scale PTC systems in rural and resource-constrained regions remains limited due to high manufacturing costs, inadequate local designs, and insufficient experimental data on performance under African climatic conditions. This study presents the novel design, fabrication, and experimental evaluation of a low-cost small-scale PTC prototype specifically developed for the climatic conditions of Alice, South Africa. Unlike conventional systems primarily optimized for large-scale industrial applications, the proposed prototype integrates locally adaptable design parameters, including a 90° rim angle and a compact aperture width of 1.072 m, to enhance thermal performance while reducing fabrication complexity and material costs. The thermal performance of the system was experimentally evaluated using a CR1000 data acquisition system to continuously monitor solar irradiance, inlet and outlet fluid temperatures, ambient temperature, and wind conditions under real outdoor operating environments. The prototype achieved a peak thermal efficiency of 35% under a maximum global horizontal irradiance (GHI) of 470 W/m^2, demonstrating the technical feasibility of decentralized solar thermal energy systems for small-scale applications. The study further provides a detailed assessment of the influence of meteorological parameters on collector performance, revealing that solar irradiance is the dominant factor governing thermal output. In contrast, wind-induced convective heat losses substantially reduce system efficiency. The novelty of this work lies in the experimental validation of a cost-effective PTC design under South African climatic conditions, along with the identification of practical performance-enhancement strategies, including selective absorber coatings and improved thermal insulation, for small-scale solar thermal applications.

Keywords: small-scale solar collector; renewable energy; efficiency; uncoated absorbers

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1. Introduction

Background

Parabolic trough collectors (PTCs) are among the most mature concentrating solar power technologies, capable of delivering medium-temperature thermal energy for industrial process heat, desalination, and power generation. Their performance depends on optical concentration efficiency, absorber characteristics, heat transfer fluid selection, and tracking mechanisms [1,2].

Recent studies have focused on structural optimization to reduce cost and improve mechanical stability. Advanced designs, such as torque box and space tube configurations, have demonstrated improved structural integrity while maintaining low material usage [3]. In addition, numerical modeling and finite element analysis have enabled the optimization of collector geometries that minimize deflection and optical misalignment [4].

Thermal performance enhancement has also been widely investigated through improved receiver configurations, nanofluids, and internal fins. Selective coatings and evacuated receiver tubes have significantly increased optical absorption and reduced thermal losses [5]. However, such advanced technologies increase system costs, potentially limiting deployment in resource-constrained environments.

Moreover, parabolic trough solar collectors (PTSCs) are critical for concentrated solar power systems, providing efficient thermal energy generation at moderate temperatures. Research has focused on enhancing PTSC performance in various ways. Furthermore, other receiver designs, such as cavity receivers with tetragonal pyramidal elements, have been examined, demonstrating enhanced heat exchange capacities [6]. Furthermore, combining internal longitudinal fins with nanofluids such as Al_2O_3-Syltherm 800 increased thermal efficiency by up to 7.25% [7]. Structural optimization studies have also been done, emphasizing the importance of design in lowering costs and enhancing performance, with the Torque Box and Space Tube structures indicating potential for future improvement [8]. Finally, using correlations for thermal modeling can significantly impact collector efficiency, underscoring the importance of precise modeling methodologies to minimize errors in performance forecasts [9].

Several studies have focused on various fluids used in parabolic trough collectors (PTCs) to improve efficiency and performance. Water, thermal oils such as Hytherm 600 and Therminol 55, liquid sodium, and gas–solid suspensions such as argon–Al_2O_3, carbon dioxide–Al_2O_3, and air–Al_2O_3 have all been studied as heat transfer fluids (HTFs) in PTCs [10–13]. Various investigations examined how different fluids affected the collectors' thermal efficiency, operating temperature range, required pumping power, and overall system efficiency. Furthermore, parametric analyses have been conducted to evaluate the impact of design variables, including inlet temperature, mass flow rate, collector width, and ambient temperature, on PTC performance variables, underscoring the significance of these factors in optimizing parabolic trough collector design [14].

Parabolic trough collectors often use sun-tracking systems to maximize solar energy capture. Various sun-tracking modes have been investigated, including fully automated, semi-automatic, and stationary designs, which substantially affect collector thermal performance [15,16]. These tracking systems are crucial for achieving high efficiency in concentrating solar systems, such as parabolic trough collectors. They are widely used in power generation, industrial heat production, water desalination, and cooling operations [17]. The tracking mechanisms might range from two-axis sun-tracking systems in residential applications to mono-axis tracking systems with linear-actuator-driven linkages in larger installations [18,19]. Furthermore, creative designs, such as concrete shell collectors, have been developed, providing an alternative to standard parabolic troughs and featuring novel tracking methods, including axial rotation or lateral motion.

Sun trackers in parabolic trough collectors play a vital role in enhancing the performance of solar collectors. Research has demonstrated that the thermal efficiency of Parabolic Trough Collectors (PTCs) is strongly influenced by the effectiveness of the solar tracking mechanism and the optical alignment of the reflector system. Studies have shown that semi-automatic and real-time tracking configurations can significantly improve the performance of PTC systems compared to fixed or conventional one-axis tracking approaches by continuously maintaining optimal solar alignment [20].

In PTC applications, the angle of incident solar radiation directly affects reflector efficiency, absorptivity, and transmissivity, leading to measurable thermal losses when the collector is not accurately aligned with the sun [21]. Consequently, microcontroller-based real-time sun-tracking systems have been widely adopted to ensure that the parabolic reflector remains continuously perpendicular to incoming solar rays, thereby maximizing solar-to-thermal energy conversion efficiency [22].

Unlike electric heating systems, which rely on grid electricity or fossil-fuel-based power generation, PTC solar collectors utilize renewable solar energy to produce thermal energy for water heating, steam generation, and industrial process heating. This makes PTC systems particularly attractive for low-cost and rural applications where electricity access may be limited or unreliable. Furthermore, replacing electric heating with PTC technology reduces operational energy costs, lowers greenhouse gas emissions, and enhances energy sustainability. Therefore, improving the optical and tracking performance of PTC systems is essential for achieving higher thermal efficiencies and strengthening their viability as an alternative renewable heating technology.

2. Performance of the PTC Prototype

Several favorable aspects distinguish the performance of the parabolic trough collector (PTC) prototype developed in this study. The system demonstrated stable thermal energy generation under varying solar conditions, indicating reliable operational performance for low-temperature solar thermal applications. The prototype demonstrated effective solar heat concentration, enabling the receiver tube to attain and maintain elevated water temperatures suitable for domestic and small-scale industrial use. In addition, the use of passive solar energy eliminates risks associated with electrical overheating, combustion, and fuel-based emissions, thereby enhancing operational safety and environmental sustainability [23].

Furthermore, integrating monitoring and solar-tracking mechanisms into PTC systems can simplify performance evaluation and improve overall collector efficiency. Automated or semi-automated tracking approaches reduce manual adjustment requirements, improve solar alignment accuracy, and enhance the consistency of thermal energy capture throughout the day [24]. These features reduce operational complexity, lower maintenance requirements, and improve system reliability, making parabolic trough solar collectors attractive for low-cost renewable energy applications in rural and decentralized environments.

Furthermore, PTC cleaning equipment enhances the cleaning process by effectively removing dirt and dust from PTC heating parts, thereby preventing impaired radiating effects, facilitating simple operation, and ensuring high practicability and rapid cleaning [25]. The PTC material exhibits excellent conductivity and temperature-sensitive properties, ensuring open-circuit protection at high temperatures without compromising average conductivity, thereby enhancing device safety performance [26]. Furthermore, a PTC unit for a vehicle heater demonstrates improved heat-radiation performance and durability, preventing overheating and overload while lowering production costs [27].

Although extensive research exists on large-scale PTC systems, limited studies focus on locally fabricated, small-scale prototypes suitable for rural or semi-urban African environments. Therefore, this study aims to design, manufacture, and experimentally evaluate a low-cost PTC prototype under the climatic conditions of Alice, South Africa.

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3. Methodology

3.1. Finding the Curvature of the Collector

The experimental evaluation of the fabricated parabolic trough collector (PTC) prototype was conducted under outdoor climatic conditions in Alice, South Africa, to assess its thermal performance under real operating environments. The prototype, designed with a 90° rim angle and an aperture width of 1.072 m, consisted of a stainless-steel reflective surface, a centrally positioned absorber tube, and a manual single-axis solar tracking mechanism to maintain optimal solar alignment throughout the testing period. Experiments were performed over several clear-sky days between 09:00 and 16:00 to ensure sufficient solar irradiance and stable environmental conditions for data acquisition. Water was used as the working fluid and circulated continuously through the absorber tube during operation. A Campbell Scientific CR1000 data logger was employed to monitor and record all experimental parameters at regular intervals, including solar irradiance, ambient temperature, inlet and outlet fluid temperatures, and wind speed. Solar irradiance was measured with a calibrated pyranometer, and temperature was measured with calibrated K-type thermocouples connected to the data acquisition system. Wind speed was measured with an anemometer near the experimental setup to evaluate the influence of convective heat losses on collector performance. Before experimentation, all sensors and measuring instruments were calibrated according to manufacturer specifications and verified against standard laboratory instruments to minimize systematic measurement errors and improve data reliability. The thermal performance of the collector was evaluated by determining the useful heat gain and the instantaneous thermal efficiency from experimentally measured temperature differences, solar irradiance, and the collector aperture area. Repeated experiments were conducted to ensure consistent, reproducible results across varying meteorological conditions. Figure 1 illustrates the geometric configuration and main dimensions of a parabolic trough collector (PTC) cross-section.

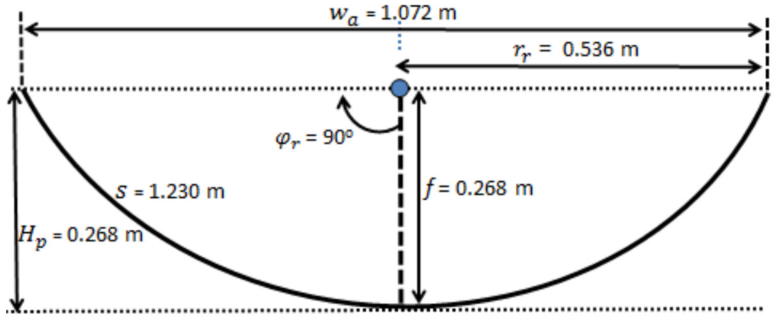

Figure 1. The reflector's values. The shapes, lines, symbols, and colors each represent specific structural and optical characteristics of the collector. Black Curved Shape (Parabolic Curve): The large line represents the parabolic reflector surface. This shape is designed to reflect incoming solar radiation toward a single focal line where the receiver tube is positioned. The parabola ensures that sunlight striking the reflective surface is concentrated efficiently at the focal point. Grey Shaded Area: ey region represents the reflective aperture area of the collector. This is the active surface that intercepts and reflects solar radiation toward the focal region. Horizontal Top Line (Wa = 1.072 m): p horizontal dimension line indicates the aperture width (Wa) of the collector. This is the total opening width through which solar radiation enters the trough. Vertical Dashed Line at the Center: Vertical dashed line represents the axis of symmetry of the parabola. It divides the trough into two halves and passes through the focal point and the vertex of the parabola. Blue Circular Point: ue point indicates the focus (focal point) of the parabola, where the receiver tube is typically placed to absorb concentrated solar energy. Vertical Arrow (f = 0.268 m): Implementscal length (f), which is the distance between the vertex of the parabola and the focal point. Left Vertical Dimension (Hp = 0.268 m): How'srabola depth or height (Hp), measured from the aperture line to the lowest

point (vertex) of the parabola. Horizontal Arrow (rr = 0.536 m): Horizontalce labeled (rr) represents the radius from the centreline to the edge of the aperture, equal to half of the aperture width. Curved Arrow (φr = 90°): The indicated(φr) of the parabolic trough. The rim angle describes the angular extent of the reflector relative to the focal axis and influences the concentration ratio and optical performance. Inclined Dimension Line (S = 1.230 m): ine represents the arc length of the parabolic reflector surface from the edge to the vertex. It corresponds to the actual length of the reflector material required for fabrication. Black Dashed Horizontal Lines: dashed lines are reference construction lines used to indicate the aperture plane and geometric alignment of the collector dimensions.

3.2. Materials, Equipment, and Specifications

The mechanical support unit's metal bars, copper tubes, and hose pipes were purchased from local hardware stores in the Eastern Cape. A complete prototype system was fabricated to save overall construction costs. Table 1 below shows the components and their descriptions of the entire frame attached to the support structure.

Table 1. Components and description of the complete frame of the PTC.

Component	Description	Estimated Price (USD)
Parabolic Reflector Bars	4 flat bars, each 1.20 m long, bent into a parabolic shape	$28–$40
Aperture Width (Wa)	1.072 m	—
Parabola Depth	0.268 m	—
Base Frame	Rectangle made of angle iron bars: 2.440 m (length) × 1.072 m (width)	$45–$70
Top Stabilizing Bar	2.440 m angle iron bar welded across the tops of the parabolic bars	$12–$20
Focal Support Bars	2 flat bars welded from the vertex of the parabola to the top angle iron bar to maintain the focal distance	$10–$18
Copper Pipe	15 mm diameter	$18–$35
Stainless Steel	1.23 m X 2.44 m	$55–$110

A pivot connected the reflecting support assembly to the mechanical base unit, allowing it to be tilted in either direction. The reflecting stainless-steel sheet was fastened to the support assembly to create a parabolic collector.

Geared levers were installed to rotate and rigidly secure the collector's support at the desired angle, with the collector perpendicular to the sun's position using a single-axis sun tracker. Figure 2 shows the parabolic trough collector installed in Alice, South Africa.

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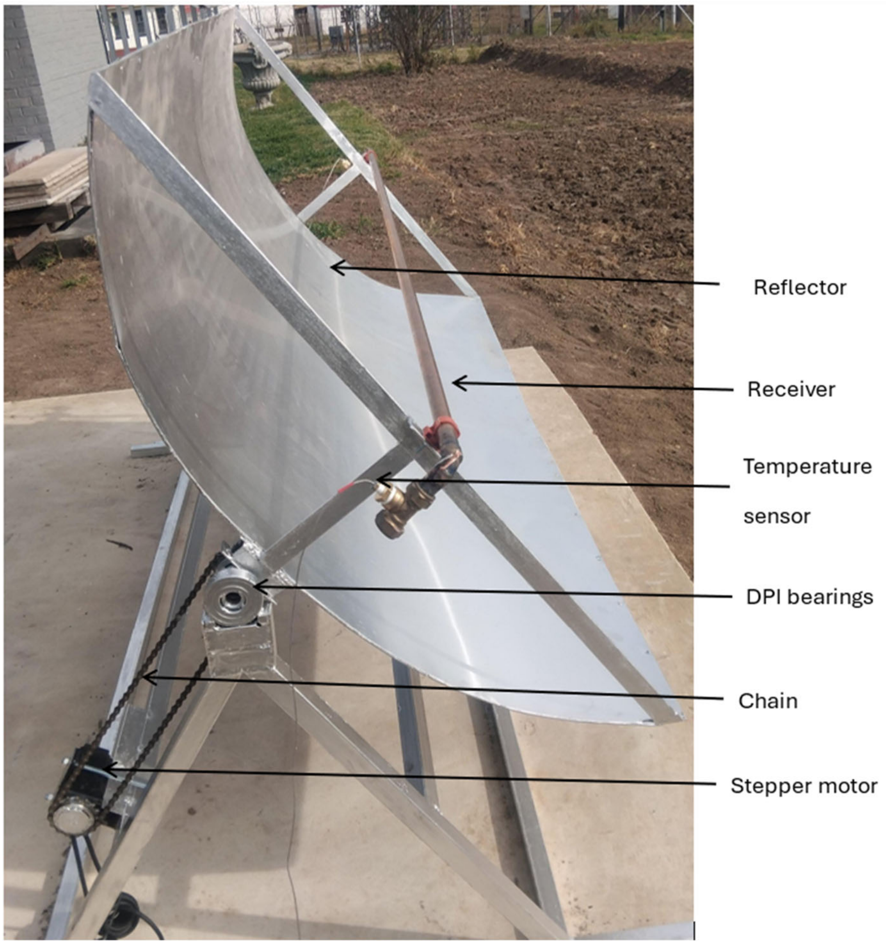

Figure 2. The parabolic trough collector installed in Alice, South Africa.

To measure the performance of the PTC prototype, the following equations were used:

3.2.1. Carnot Efficiency

$$\eta_c = 1 - \frac{T_c}{T_H} \tag{1}$$

3.2.2. Useful Heat Gain

$$Q_u = \dot{m}C_p(T_{out} - T_{in}) \tag{2}$$

3.2.3. Useful Heat Gain per Unit Area

$$q_u = \frac{Q_u}{A_c} \tag{3}$$

3.2.4. Instantaneous Efficiency

$$\eta = \frac{Q_u}{GHI \times A_c} \tag{4}$$

3.2.5. Absorbed Flux

$$S = \alpha \times GHI \tag{5}$$

3.2.6. Overall Heat Loss Efficiency

$$U_L = \frac{S - q_u}{T_{AVG} - T_a} \tag{6}$$

3.2.7. Average Temperature

$$T_{avg} = \frac{T_{in} + T_{out}}{2} \tag{7}$$

3.2.8. Useful Heat Gain Rate per Equation Form

$$Q_u = A_c F_R [S - U_L (T_i - T_a)] \tag{8}$$

3.2.9. Collector Heat Removal Factor (F_R)

$$F_R = \frac{\dot{M} C_P}{A_C U_L} [1 - e^{-\frac{A_C U_L F'}{\dot{M} C_P}}] \tag{9}$$

3.2.10. Useful Heat Gain per Equation Form

$$Q_U = A_C F_R [S - U_L (T_{in} - T_a) \tag{10}$$

4. Results and Discussion

This paper presents the findings from an experimental setup utilizing a copper tube. The systems' optical, thermal, and Carnot efficiencies were computed using experimental data obtained on various days. The Fort Beaufort Climatological Station provided data on air temperature, global horizontal irradiance, and wind speed in January 2025. Table 2 below shows the initial values and parameters.

Table 2. All the initial values and parameters used to estimate the system's efficiency.

Component	Symbol	Value
Mass flow rate	$\dot{M}$	0.0012 kg/s
Specific heat capacity of water	C_p	4180 J/kg·K
Global horizontal irradiance	GHI	470 W/m^2
Inlet temperature	T_{in}	26 °C
Outlet temperature	T_{out}	65 °C
Thermal conductivity	K_p	385 W/m·K
Inner diameter	D_o	0.02 m
Inner diameter	D_i	0.022 m
Collector aperture area	A_c	1.2 m^2
Ambient temperature	T_a	25 °C
Reflectivity of stainless steel	ρ	0.55

Convective heat transfer, optical concentration, and overall system efficiency are essential factors in solar energy conversion, examined in this study. The goal is to determine how the collector's thermal and optical efficiency is affected by variables such as mass flow rate, global horizontal irradiance (GHI), and the temperature differential between the fluid and the surrounding air.

The subsequent analysis integrates empirical data and thermodynamic principles to derive parameters, including useful heat gain (Q_u), heat loss coefficient (U_L), heat removal factor (F_R), and collector efficiency (η). These are compared to standard models, including the Hottel–Whillier–Bliss equation, which represents the instantaneous efficiency of solar thermal collectors. Additionally, the internal convective heat transfer performance is evaluated through the Reynolds (Re) and Nusselt (Nu) numbers, as well as the internal heat transfer coefficient (h_i), providing insight into the fluid-dynamic regime and its implications for system optimization.

The table presents a comparison of the thermal performance of an evacuated tube solar collector installed in Gödöllő and the fabricated parabolic trough collector (PTC) prototype tested in Alice. Although both systems utilized water as the heat transfer fluid, the evacuated tube collector operated under substantially higher solar irradiance conditions of 1130 W/m^2 and achieved an outlet temperature of 80 °C. In contrast, the PTC prototype achieved an outlet temperature of 65 °C with a peak thermal efficiency of 35% under a lower global horizontal irradiance of 470 W/m^2. Despite its smaller aperture area and lower irradiance conditions, the PTC prototype demonstrated satisfactory thermal performance, indicating its capability for small-scale solar thermal applications. The lower efficiency and outlet temperature of the PTC system can be attributed to the use of an uncoated receiver tube, a non-evacuated absorber configuration, and increased convective heat losses. Nevertheless, the results confirm that the developed prototype can effectively harness solar energy under moderate climatic conditions while maintaining a simple, low-cost design suitable for decentralized applications. Table 3 below compares the thermal performance of an evacuated tube solar collector installed in Gödöllő with that of the fabricated parabolic trough collector (PTC) prototype tested in Alice.

Table 3. A comparison of the thermal performance of an evacuated tube solar collector installed in Gödöllő and the fabricated parabolic trough collector (PTC) prototype tested in Alice.

Collector Type	Location/ Setting	Aperture Area (m^2)	Peak Thermal Efficiency (%)	Inlet Temperature (°C)	Outlet Temperature (°C)	Global Horizontal Irradiance (W/m^2)	Heat Transfer Fluid
Evacuated Tube Solar Collector	Gödöllő, Hungary	2.2	Not in source	Not in source	80	1130	Water
Parabolic Trough Collector (PTC) Prototype	Alice, South Africa	1.2	35	26	65	470	Water

4.1. Effect of GHI on the Ambient Temperature

Global Horizontal Irradiance (GHI) plays a critical role in governing ambient temperature variations in solar-rich regions such as Alice, South Africa. Increased GHI during daytime hours leads to higher surface and air temperatures due to enhanced solar energy absorption. The response of ambient temperature typically exhibits a time lag due to atmospheric and ground thermal inertia. Understanding this relationship is essential for evaluating the operating environment of parabolic trough collectors. Ambient temperature directly influences thermal losses and overall system efficiency in PTC installations. Figure 3 below shows the ambient temperature and solar irradiance over time.

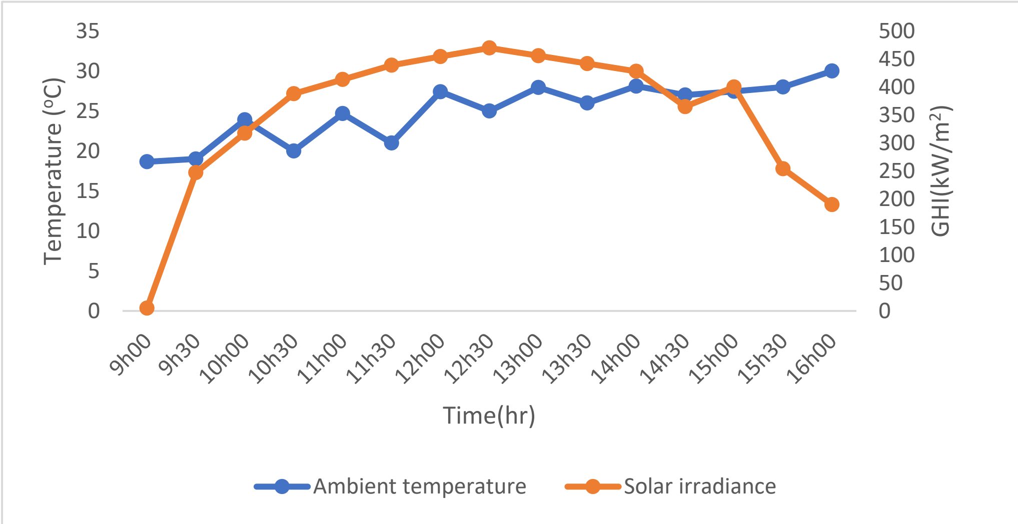

Figure 3. The ambient temperature and solar irradiance over time.

The first graph illustrates the temporal variation of inlet temperature, outlet temperature, temperature rise (ΔT), and Global Horizontal Irradiance (GHI) between 09:30 and 16:00. Solar irradiance increases steadily from 09:30, reaching a peak around 12:30–13:00 at approximately 470 W/m^2, before declining toward 16:00. Correspondingly, the outlet temperature rises from approximately 32 °C at 09:30 to a maximum near 65 °C at 12:30, after which it gradually decreases. The inlet temperature shows a relatively modest increase throughout the day, rising from about 22 °C to approximately 29–30 °C by late afternoon. The temperature difference (ΔT) follows the irradiance profile, peaking at midday and declining thereafter.

The pattern clearly shows that solar radiation incidents strongly influence the collector's thermal performance. The peak temperature rise around 12:30 indicates optimal solar energy absorption and heat transfer during the period of maximum irradiance. After 14:30, the decline in GHI reduces outlet temperature and ΔT, highlighting the dependence of useful heat gain on solar availability. This behavior is characteristic of solar thermal systems operating under direct irradiance conditions, where collector output closely tracks solar intensity.

4.2. Effect of Wind Speed on Ambient Temperature

Wind speed significantly affects ambient temperature by enhancing convective heat exchange between the ground, surrounding structures, and the atmosphere. In Alice, South Africa, moderate to high wind speeds can lower local ambient temperatures by increasing air mixing. This convective cooling alters the thermal boundary conditions under which parabolic trough collectors operate. Variations in ambient temperature due to wind influence heat loss rates from the receiver tube. Consequently, wind speed is an essential environmental parameter in PTC performance assessment. Figure 4 below shows the ambient temperature and wind speed over time.

The second graph presents inlet temperature, outlet temperature, temperature rise, and wind speed over the same period. Wind speed remains relatively high, fluctuating between approximately 1 and 6.9 m/s (as labeled), with slight increases toward midday. The outlet temperature increases from 09:30 to 12:30, reaching a maximum near peak solar hours, then decreases toward 16:00. The inlet temperature remains comparatively stable, showing a gradual upward trend throughout the day.

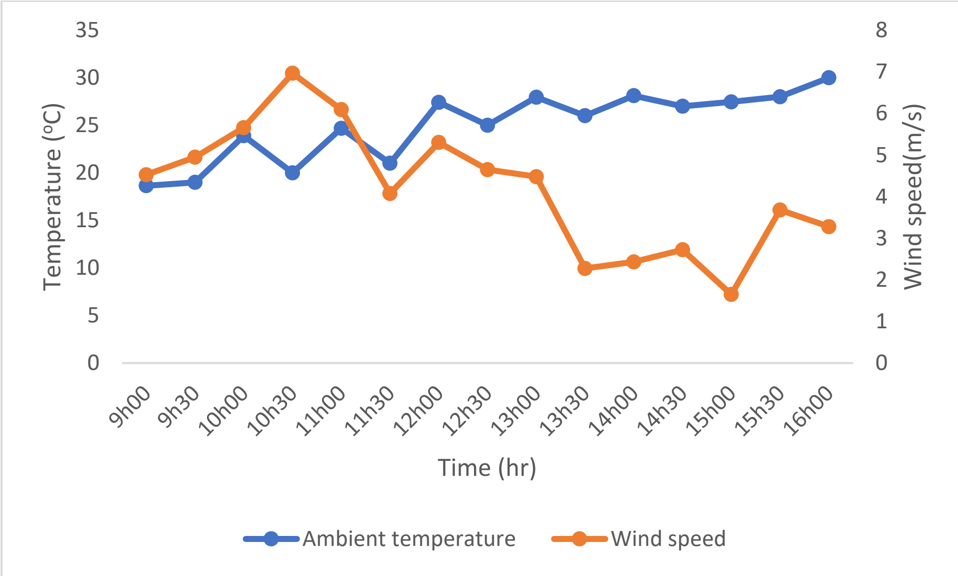

Figure 4. The ambient temperature and wind speed over time.

Although solar irradiance appears to be the primary driver of temperature rise, wind speed introduces convective heat losses that moderate collector performance. Around 14:30–16:00, despite moderate wind speeds, a noticeable drop in outlet temperature and ΔT occurs. This suggests that convective cooling of the receiver reduces thermal efficiency in the afternoon. In solar thermal systems, increased wind speeds enhance external heat transfer coefficients, thereby increasing heat losses from the absorber surface and reducing the useful heat output.

4.3. Effect of GHI on the Outlet Temperature

The outlet temperature of a parabolic trough collector is strongly dependent on the available Global Horizontal Irradiance. Higher GHI levels result in increased absorbed solar energy, leading to elevated heat transfer to the working fluid. In Alice, South Africa, high solar availability enables the PTC system to achieve significant increases in outlet temperature during peak irradiance periods. The outlet temperature response reflects the effectiveness of solar concentration and absorption mechanisms. This parameter is critical for evaluating the thermal output and usability of the collected solar energy. Figure 5 below shows the temperature and irradiance over time.

The third graph shows the relationship between ambient temperature and wind speed from 09:00 to 16:00. Ambient temperature increases progressively from approximately 18–19 °C in the morning to nearly 30 °C by 16:00. Wind speed fluctuates within a range without a clear upward or downward trend. The ambient temperature exhibits a generally increasing pattern with minor oscillations, particularly around 10:30 and 11:30.

The absence of a strong direct correlation between wind speed and ambient temperature suggests that solar irradiance plays a more dominant role in ambient warming. While wind may influence localized cooling effects, the steady increase in ambient temperature throughout the day reflects cumulative solar heating of the surrounding environment. For solar thermal systems, rising ambient temperatures reduce the temperature gradient between the absorber and the surroundings, thereby slightly reducing convective heat losses and improving thermal efficiency during peak hours.

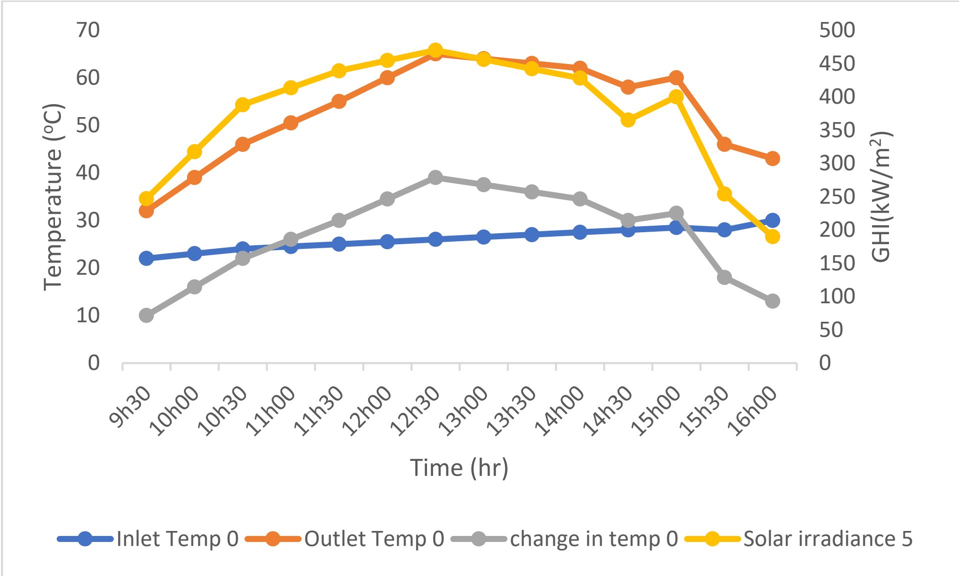

Figure 5. The temperature and irradiance over time.

4.4. Effect of Wind Speed on the Outlet Temperature

Wind speed influences the outlet temperature of a parabolic trough collector by affecting convective heat losses from the receiver tube. Increased wind speeds enhance external convection, thereby reducing the net heat retained within the absorber. In the climatic conditions of Alice, South Africa, wind-induced cooling can noticeably suppress outlet temperature despite high solar irradiance. This interaction highlights the importance of wind shielding and receiver insulation in PTC design. Understanding wind effects is essential for accurate thermal performance prediction. Figure 6 below shows the time series of temperature and wind speed.

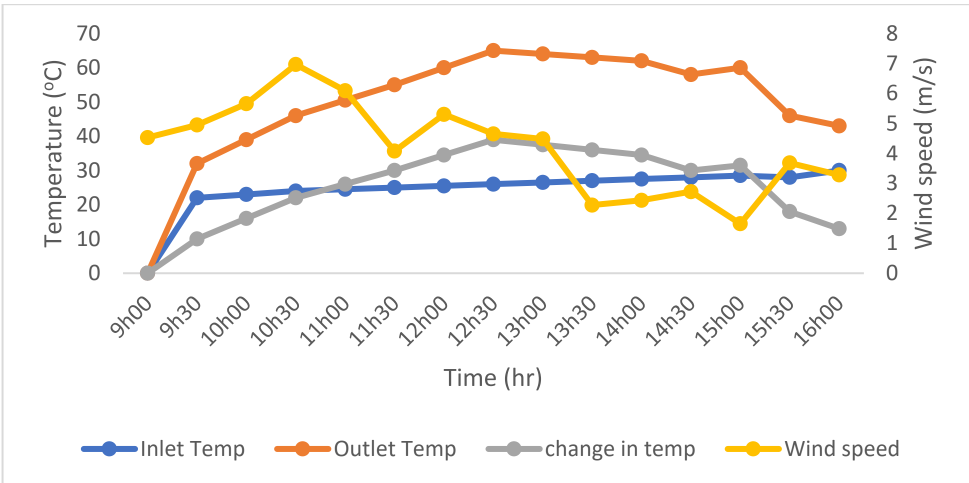

Figure 6. The time series of temperature and wind speed.

The outlet temperature increased steadily from approximately 32 °C at 09h30 to a maximum value of about 65 °C at 12h30, indicating effective solar energy absorption and heat transfer within the parabolic trough collector system. In contrast, the inlet temperature increased gradually throughout the day, rising from approximately 22 °C to about 30 °C by 16h00. Consequently, the temperature difference between the inlet and outlet streams increased significantly during the morning hours, reaching a peak of approximately 39 °C around midday. This behavior suggests that the collector achieved its highest thermal performance during periods of elevated solar irradiance and favorable atmospheric conditions.

The influence of wind speed on collector performance is also evident from the graph. Wind speed increased during the morning, reaching values above 6 m/s between 10h00 and 13h00, before declining in the late afternoon. Although moderate wind conditions can help maintain stable operating temperatures, higher wind velocities are generally associated with increased convective heat losses from the absorber surface and the receiver tube. This effect is reflected in the reduction in the temperature difference after 13h00, with the outlet temperature gradually decreasing despite relatively stable inlet temperatures. A sharp decline in outlet temperature is observed after 15h00, with the temperature difference reducing to approximately 13 °C by 16h00. This decline can be attributed to reduced solar irradiance in the late afternoon and to enhanced thermal losses driven by ambient conditions. Overall, the graph confirms that the thermal efficiency and heat gain of the solar collector are strongly dependent on both solar availability and meteorological parameters, particularly wind speed.

4.5. Carnot Efficiency (η_c)

Carnot efficiency represents the theoretical maximum efficiency achievable by a thermal system operating between two temperature reservoirs. For a parabolic trough collector, it defines the upper limit of energy conversion based on outlet and ambient temperatures. Although unattainable in practice, Carnot efficiency provides a valuable benchmark for evaluating system performance. In PTC installations in Alice, South Africa, this parameter helps contextualize actual efficiency gains under local climatic conditions. It serves as a reference for assessing thermodynamic losses within the system. Figure 7 below shows the Carnot efficiency over time.

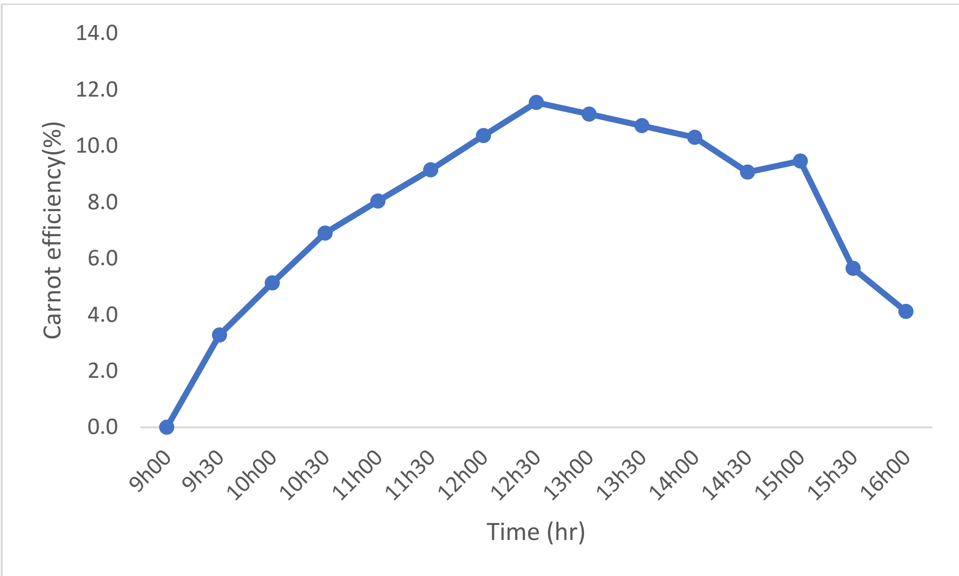

Figure 7. Carnot efficiency over time.

The Carnot efficiency reached 11.5% at 12:30, corresponding to the largest temperature differential between the receiver and the ambient environment during peak solar conditions. This reflects the theoretical upper bound on the system's thermodynamic performance at the maximum outlet temperature. As solar irradiance declined in the late afternoon, the Carnot efficiency decreased to 4.1% at 16:00, driven by reduced absorber temperatures and a smaller temperature gradient. Such variation is consistent with established thermodynamic principles governing solar thermal systems. While Carnot efficiency does not represent

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actual system performance, the observed values are typical of low- to medium-temperature solar thermal collectors.

4.6. Useful Heat Energy Output

Useful heat output quantifies the portion of absorbed solar energy effectively transferred to the working fluid. In parabolic trough collector systems, this parameter reflects the net thermal energy available for practical applications. The useful heat output depends on solar irradiance, flow rate, and thermal losses. In the high-solar-resource conditions of Alice, South Africa, PTC systems can achieve substantial useful heat gains. This metric is fundamental for evaluating system viability and energy contribution. Figure 8 below shows the useful heat output over time.

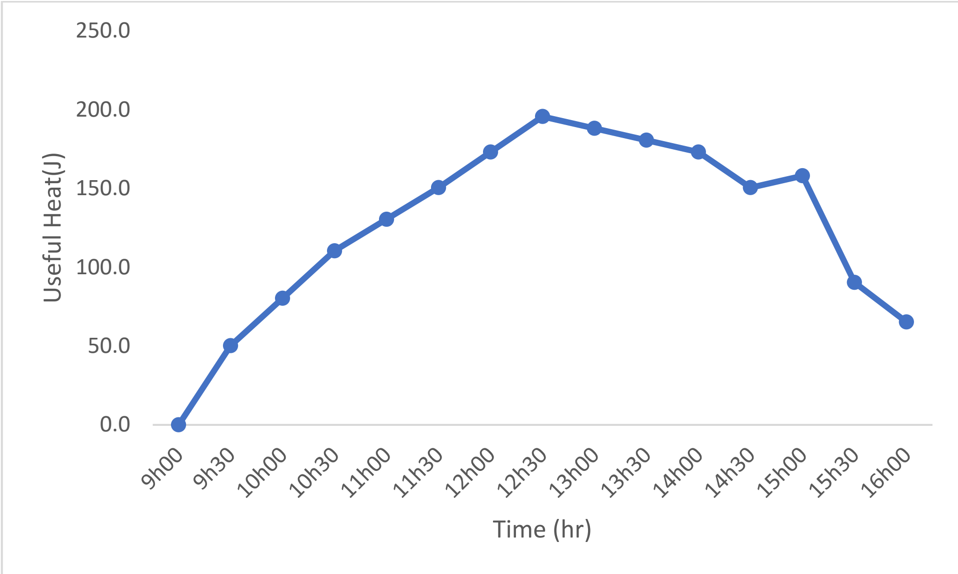

Figure 8. The useful heat output over time.

The useful heat gain reached a peak value of 195.6 W at 12:30, indicating effective conversion of incident solar energy into thermal energy under favorable irradiance conditions. This demonstrates that the collector could deliver meaningful thermal output during peak operation. Conversely, the useful heat gain declined to 50.2 W at 09:30, reflecting limited solar input during early operating hours. The reduction highlights the sensitivity of thermal output to solar availability and operating temperature. Overall, the system demonstrates moderate heat extraction capability, particularly during peak irradiance.

4.7. Optical Efficiency (η_o)

Optical efficiency represents the fraction of incident solar radiation that is successfully reflected, focused, and absorbed by the receiver tube. In parabolic trough collectors, it is influenced by mirror reflectivity, tracking accuracy, and absorber absorptivity. High optical efficiency is essential for maximizing energy capture in regions such as Alice, South Africa. Losses from misalignment, surface degradation, and shading degrade optical performance. This parameter is crucial for assessing the quality of PTC's optical design and installation. Figure 9 shows the heat gained per area over time.

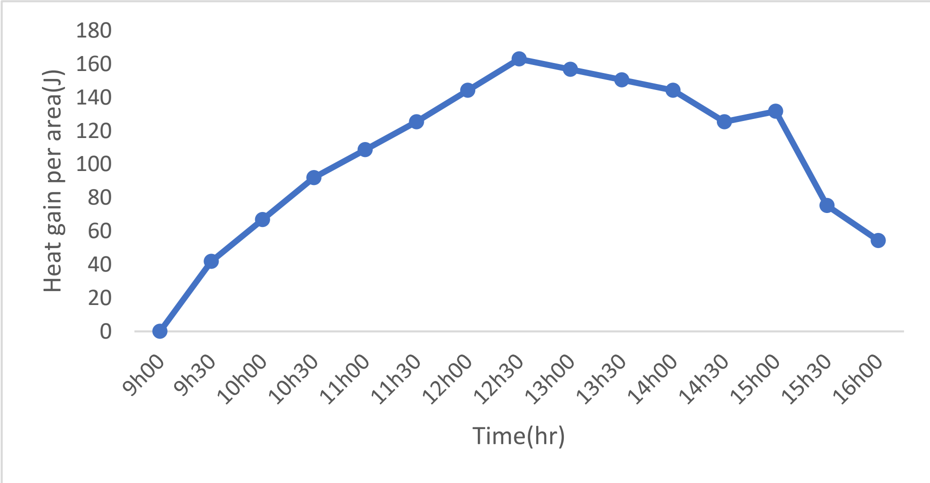

Figure 9. The heat gained per area over time.

The maximum useful heat gain per unit area was 163.02 W/m^2 at 12:30, suggesting effective utilization of the collector aperture under optimal solar conditions. This value is within the range reported for small-scale solar thermal collectors employing non-selective absorbed surfaces. At 09:30, the gain per unit area decreased to 41 W/m^2, indicating increased relative heat losses at lower irradiance levels. The strong dependence on solar intensity underscores the limitations of uncoated absorbers in low-flux conditions. Compared to selectively coated receivers reported in the literature, the per-area performance remains comparatively low.

4.8. Thermal Efficiency (η_{th})

Thermal efficiency describes the ratio of useful heat output to the total solar energy incident on the collector aperture. It provides a direct measure of the overall performance of a parabolic trough collector system. Thermal efficiency is affected by optical efficiency, heat losses, and operating temperatures. In the climatic conditions of Alice, South Africa, thermal efficiency varies throughout the day with changing irradiance and wind speed. This parameter is widely used to compare PTC performance under real operating conditions. Figure 10 below shows instantaneous efficiency over time.

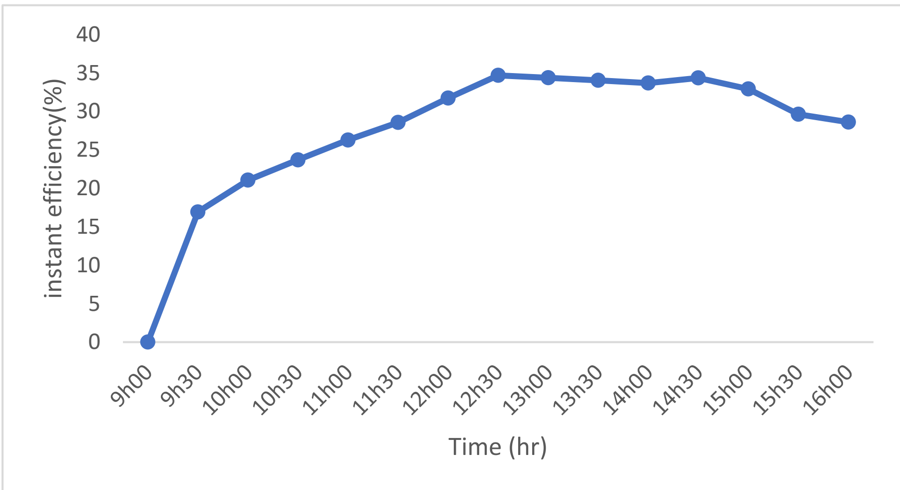

Figure 10. Instantaneous efficiency over time.

The optical efficiency reached 35% at 12:30, indicating moderate effectiveness in concentrating and absorbing incident solar radiation. Optical losses are attributed to limited mirror reflectivity, alignment inaccuracies, the absence of a selective absorber coating on the copper receiver, and heat losses through uninsulated water transport pipes. The lack of pipe insulation increased thermal losses to the surrounding environment during fluid circulation, thereby reducing the useful heat delivered to the storage system and lowering the collector's overall thermal performance. The optical efficiency decreased to 17% at 09:30, mainly due to low solar incidence angles and increased reflection losses. These values are significantly lower than those reported for commercial parabolic trough collectors, which typically exceed 60%, confirming that optical and thermal losses remain major limiting factors in the present system.

4.9. Absorber Flux

The absorbed flux peaked at 423 W/m^2 at 12:30, which closely matched the maximum Global Horizontal Irradiance and optical efficiency. This absorbed energy level supports the observed increases in outlet temperature and useful heat gain. At 16:00, the absorbed flux decreased to 171 W/m^2, reflecting reduced solar input and increased relative losses. The uncoated copper surface further reduces absorption efficiency, particularly at low irradiance. Compared with selectively coated receivers reported in the literature, the absorbed flux remains modest.

5. Uncertainty Analysis

The experimental measurements obtained during the performance evaluation of the parabolic trough collector (PTC) prototype were subject to uncertainties arising from instrumentation accuracy, environmental fluctuations, and data-acquisition limitations. To ensure the reliability of the experimental results, an uncertainty analysis was conducted for all measured and derived parameters using the root-sum-square (RSS) method of error propagation.

The directly measured parameters included ambient temperature, inlet temperature, outlet temperature, solar irradiance, and wind speed. Temperature measurements were obtained using calibrated thermocouples connected to a CR1000 data logger, with an estimated measurement uncertainty of ± 0.5 °C. Solar irradiance was measured using a pyranometer with an uncertainty of approximately ± 5 W/m^2, while wind speed was measured with an anemometer, with an uncertainty of ± 0.1 m/s.

The absorber flux uncertainty was evaluated by considering uncertainties in solar irradiance and optical concentration parameters. In contrast, the Carnot efficiency uncertainty was estimated from uncertainties in absorber and ambient temperature measurements using standard thermodynamic error-propagation methods. Table 4 below shows the estimated uncertainties associated with the measured and calculated parameters.

The uncertainty analysis indicates that the largest deviations are associated with derived thermal performance parameters due to cumulative propagation of measurement uncertainties. Nevertheless, the uncertainty levels remain within acceptable ranges for experimental investigations of solar thermal systems, thereby confirming the reliability and validity of the reported results.

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Table 4. The estimated uncertainties associated with the measured and calculated parameters.

Parameter	Instrument/Method	Estimated Uncertainty
Ambient temperature	Thermocouple	±0.5 °C
Inlet temperature	Thermocouple	±0.5 °C
Outlet temperature	Thermocouple	±0.5 °C
Temperature difference	Calculated	±0.71 °C
Solar irradiance	Pyranometer	±5 W/m^2
Wind speed	Anemometer	±0.1 m/s
Useful heat gain	Derived	±3–5%
Heat gain per area	Derived	±3–5%
Instantaneous efficiency	Derived	±4–6%
Absorber flux	Derived	±4–6%
Carnot efficiency	Derived	±2–4%

6. Discussion

The overall trends across all graphs confirm that solar irradiance is the dominant parameter influencing collector performance. The outlet temperature and temperature rise closely follow the irradiance curve, peaking around solar noon. This demonstrates effective solar energy absorption and conversion during periods of maximum GHI. The system's response aligns with established solar thermal theory, which states that useful heat gain is directly proportional to incident radiation under steady-flow conditions.

While secondary to irradiance, wind speed plays a significant role in modulating thermal efficiency through convective losses. Increased wind exposure in the afternoon coincides with declining outlet temperatures, suggesting enhanced external heat transfer from the receiver surface. Additionally, the gradual increase in ambient temperature throughout the day partially offsets thermal losses by reducing the absorber-to-ambient temperature difference. Collectively, these interactions highlight the complex balance between solar input, environmental conditions, and thermal losses in determining overall collector performance.

The results further demonstrate a clear and consistent dependence of system performance on solar irradiance, with all key performance indicators peaking near solar noon. The concurrence of maximum Carnot efficiency, useful heat gain, optical efficiency, and absorbed flux at 12:30 confirms coherent system behavior and validates the experimental trends. These findings align with established solar thermal performance theory and report the behavior of parabolic trough collectors under variable solar conditions.

However, the absolute efficiency levels remain substantially lower than those reported for coated and evacuated parabolic trough receivers. The use of an uncoated copper receiver significantly reduces optical absorptivity and increases thermal losses through radiation and convection. Previous studies have shown that selective coatings can enhance absorptivity to above 90%, leading to marked improvements in both optical and thermal efficiency.

Despite these limitations, the system demonstrates satisfactory performance as an experimental and proof-of-concept installation. Its ability to produce consistent thermal output under varying irradiance conditions highlights its functional viability and relevance for small-scale or low-cost solar thermal applications. The results emphasize the critical role of receiver surface properties in determining overall system performance.

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7. Conclusions

The experimental investigation demonstrated the feasibility of using a small-scale parabolic trough collector (PTC) for solar thermal applications in Alice, South Africa. The study confirmed that solar irradiance is the dominant factor influencing collector performance and thermal output.

7.1. Key Findings

- The outlet temperature and temperature rise increased with increasing solar irradiance and reached peak values near solar noon.
- Maximum useful heat gain, absorber flux, optical efficiency, and Carnot efficiency were observed at approximately 12:30, corresponding to the highest recorded global horizontal irradiance (GHI).
- The thermal behavior of the system followed established solar thermal theory, where useful heat gain is directly proportional to incident solar radiation under steady operating conditions.
- Wind speed significantly affected collector performance by increasing convective heat losses from the receiver surface, particularly in the afternoon.
- Increasing ambient temperature helped reduce thermal losses by lowering the temperature difference between the absorber surface and the surrounding environment.
- The experimental results showed consistent system behavior under varying weather conditions, confirming the reliability of the prototype and the measurement methodology.
- The use of an uncoated copper receiver reduced overall thermal efficiency due to lower solar absorptivity and higher radiative and convective heat losses.
- The obtained efficiency values were lower than those reported for evacuated or selectively coated receivers, highlighting the importance of advanced absorber surface treatments.
- Despite these limitations, the prototype achieved stable thermal performance and demonstrated its suitability as a low-cost experimental solar thermal system.
- The findings emphasize that receiver surface properties, thermal insulation, and environmental conditions are critical parameters affecting the overall efficiency of parabolic trough collectors.

7.2. Recommendation

- Future studies should investigate the application of selective absorber coatings to improve solar absorptivity and reduce thermal losses.
- The integration of evacuated receiver tubes and improved thermal insulation is recommended to enhance collector efficiency.
- Automatic solar tracking systems may further improve energy collection and thermal performance.
- Long-term experimental testing under different seasonal conditions is recommended to evaluate the durability and operational stability of the system.

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