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Innovative Multistage Solar Parabolic Trough Collector: Design, Development, and Thermal Performance

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A B S T R A C T

Reliance on fossil fuels has led to severe environmental challenges that require more intensive development of clean energy alternatives. A design and experimental evaluation of a novel multistage parabolic trough collector (PTC) set under Basra City's climatic conditions, southern Iraq, is presented. Four interconnected parabolic channels were designed to enhance cumulative heat gain while reducing the construction installation space. A corrugated copper tube receiver is used to increase the heat transfer surface and induce flow turbulence. A single-axis solar-tracking system was added to maximize incident solar radiation, with water flow rates of 3, 5, and 7 L/min. Conducting experimental results indicated that increasing the water flow rate reduced the outlet water temperature. The temperature gain was enhanced by 24%. The maximum temperature gain of 19 °C was recorded at 3 L/min, whereas the minimum was recorded at 7 L/min. Conversely, thermal efficiency increased with flow rate, reaching 82% at 7 L/min, corresponding to an improvement by 15-18%. The heat transfer coefficient was boosted up to 35%. The pressure drop was measured between 0.42 and 0.53 bar. These findings confirm the potential of the new design to enhance efficient energy capture, and a quantitative comparison with the traditional single-stage SPTC.

1. Introduction

Renewable energy is today a major resource worldwide, providing sustainable heat, power, and fuels for the smallest to the largest needs [1]. Unconventional sources of energy are widely utilized across various sectors, including both commercial and residential structures, to produce hot water and heat interior spaces [2,3]. Solar power is a significant energy source that is pure, inexhaustible, and secure. Despite producing power from solar or thermodynamic plants, it emits no hazardous emissions. It also reduces greenhouse gas emissions, costs, and pressure on power grids, promoting a more resilient energy infrastructure [4]. Solar radiation is a high-temperature, high-exergy energy source, with an irradiance of about 63 MW/m2. However, the solar energy flux on the Earth's surface is considerably reduced by the effect of the Sun-Earth geometry to

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about 1 kW/m² [5,6]. Therefore, flat-plate solar collectors are incapable of working at temperatures above 100°C. The disadvantage of low solar radiation intensity can be overcome by using concentrating solar systems. Solar concentrators such as parabolic troughs (concentrators) provide efficiencies of around 12%, which is better than those of standard flat-panel collectors at much higher working temperatures [7]. When an incident radiant solar ray beam strikes a trough and enters a parabolic collector, its energy is concentrated along the focal line center, absorbed by the receiver, and converted into thermal energy, which is then used to power a receiver tube. SPTC technology is a great and valuable option because it depends on the sun [8]. It is characterized by several advantages, including high energy capacity, high efficiency, multiple uses, long life, and durability against moisture. It also has drawbacks such as the use of moving parts, the deformation of the receiver over time, the high maintenance cost of the tracking system, or manual adjustment to keep the reflected solar radiation in the correct focal point (focal line), and the large, required land area [9,10]. A (PTC) concentrator , like the one in Fig.1, is used in solar thermal power generation.

Fig .1 photograph of parabolic trough collector (concentrator) [11]

The development of solar collector designs has taken on great importance worldwide to better meet thermal needs. Using a sun tracker will enhance the solar collector efficiency throughout the day, especially if a 3-D collector type is used. Also, the modification of the receiver geometry with corrugated tubes significantly enhances the thermal performance of solar thermal parabolic collectors (concentrator) [12]. Various experimental investigations have been conducted using different designs of parabolic trough collectors in water heating systems to maximize thermal efficiency through the effective utilization of solar energy.

The study conducted design, fabrication, and comprehensive experimental evaluation of a (PTC) concentrator system adapted to Tunisian climatic conditions. The prototype incorporated a stainless steel, selectively coated absorber tube enclosed within an evacuated borosilicate glass envelope, mounted on a galvanized steel support structure with manual single-axis (north–south) solar tracking. Under clear sky conditions, the system achieved a peak instantaneous thermal efficiency of 60.04 %, whereas mean efficiencies under representative sunny and cloudy days were 41.09 % and 28.91 %, respectively [13]. At the Indian Institute of Technology Madras, experimental work was conducted on a (PTC) concentrator with a rim angle of 80.2°. The system was tested with two types of receivers, namely an evacuated receiver (ER) and a non‑evacuated receiver (NER), following ASHRAE 93‑2010 standards. Results showed that the peak optical efficiency reached about 72 % for the ER and 68 % for the NER, while the maximum thermal efficiency was 66 % and 64 %, respectively, at a mass flow rate of 0.12 kg/s. [14]. A series of experimental tests was conducted to evaluate the thermal performance of a newly developed (PTC) concentrator under real outdoor conditions in Tunisia. The system incorporates a bi-axial solar tracking mechanism and a glass-covered absorber tube designed to minimize thermal losses. The experimental results demonstrated a peak outlet temperature of 179 °C and a maximum instantaneous thermal efficiency of 73.5%. Compared to conventional mono-axial designs without a glass envelope, the new configuration achieved a 33% increase in daily energy gain and an 8.9% improvement in overall thermal efficiency [15]. A multistage parabolic trough solar collector was designed and constructed, consisting of five identical channels, equipped with a dual‑axis solar tracking system using a sunlight sensor and two servo motors to maintain optimal alignment with the sun throughout the day. Experimental tests were conducted in Baghdad over 15 days under open loop operation at four water flow rates (3, 5, 7, and 9) L/min. Results indicated that lower flow rates produced the highest temperature differentials, heat gain, and convective heat transfer coefficients, leading to thermal efficiency improvements exceeding 70 % compared to a single‑channel collector [16]. The study investigated the performance of an LS‑2 parabolic trough collector integrating internal longitudinal fins and a partial internal radiation shield, applied individually and in combination, using Syltherm 800 as the working fluid. Results showed that fins consistently enhanced thermal performance, the radiation shield was advantageous at elevated operating temperatures, and the combined configuration yielded the greatest improvement, achieving a 2.41 % thermal efficiency gain at an inlet temperature of 650 K and a flow rate of 150 L min^{-1} compared with the reference smooth‑tube design [17]. The experimental study was conducted to design and optimise a parabolic trough collector for domestic thermal applications. The fabricated system achieved a peak thermal efficiency of 63.7% under optimal solar irradiance and flow conditions. Performance evaluation confirmed stable heat gain and effective solar concentration, validating its suitability for household water heating [18]. An experimental and numerical analysis of a (PTC) concentrator was carried out to evaluate the effects of heat transfer fluid (HTF) type, mass flow rate, and vacuum insulation on thermal performance. Three HTFs (Syltherm 800, S2 oil, and water) were tested across flow rates from 0.0372 to 0.1072 kg/s and solar irradiance levels between 400 and 900 W/m². Results showed that Syltherm 800 achieved the highest thermal performance, with up to 35.1% increase in absorber temperature at high solar radiation. Vacuum insulation significantly reduced heat loss, improving efficiency by 6.7% for Syltherm 800 and 8.3% for S2 [19]. The investigation of an experimental study focused on enhancing the performance of (PTC) concentrator innovative and low-cost receiver designs. Three configurations were tested: a conventional copper tube, a black-painted copper tube, and a tube filled with paraffin wax as a phase change material (PCM). The PCM- filled design achieved the highest thermal and exergy efficiencies, with values of 16.9% and 2.3%, respectively, representing a 56.8% increase in thermal energy compared to the conventional SPTC. The inclusion of paraffin waxes improved energy storage, stabilised output under variable solar conditions, and reduced CO_2 emissions by over 50%, demonstrating the potential of simple design enhancements for sustainable solar energy applications [20]. An experimental study in Tunisian climate was undertaken to assess a newly designed (PTC) concentrator featuring a bi-axial tracking system and a glass-covered absorber tube. The collector's performance was compared against mono- and bi-axial systems without glass envelopes under summer and winter conditions. Results showed that the new design achieved a maximum temperature of 179 °C, a 33% increase in useful daily energy gain, and up to 8.9% higher thermal efficiency [21].

2. Aim of The Study

- ❖ Design a new multichannel parabolic collector to maximize the collector's incident sunlight with minimum construction area.
- ❖ Using a corrugated copper tube as a receiver to enhance the heat transfer area, consequently increasing heat gain and thermal efficiency.
- ❖ Using the sun tracker to collect the maximum sunlight incident rays.

3. Experimental work

This study presents the experimental work on a new design and constructed parabolic trough collector, which applies multiple enhancement methods.
A novel design of the SPTC system consists of the following parts, as shown below in Figure 2.

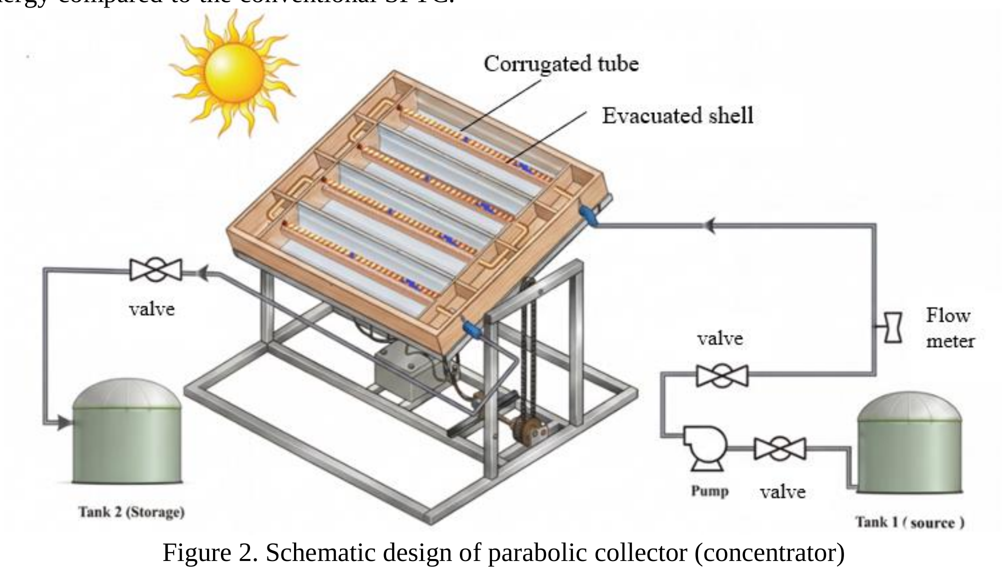


Figure 2. Schematic design of parabolic collector (concentrator)

The corrugated tube is used as the receiver to increase the surface area of heat transfer, and a sun tracker is utilised to collect the maximum amount of sunlight incident on the Earth. This study was conducted at Basra city, south of Iraq, from May 2025 to July 2025. The experimental data were recorded from 7 am to 9 p.m.

3.1 Reflector parabola design

The parabolic trough concentrator system is mainly composed of a reflecting surface, the receiver tube, and a support structure. The SPTC is composed of four channels connected; each channel has dimensions described in Table 1 and the specification properties in Table 2. A parabolic arc was drawn using the software Parabola Calculator 2.0, as presented in Fig. 3.

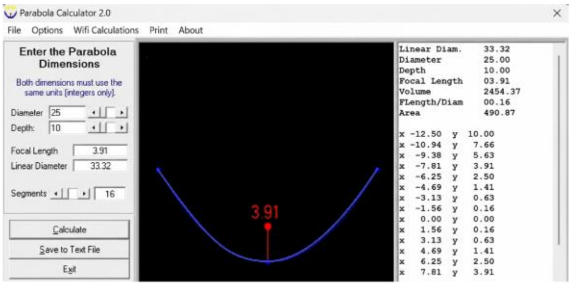


Figure 3. channels graphical design

After designing the SPTC, the executable-designed rig will have the Following shape. As shown below in Figure 4.

T: Thermocouple position

Figure 4. SPTC system on the supporting construction showing thermocouple locations

Table 1. The characteristic of channel

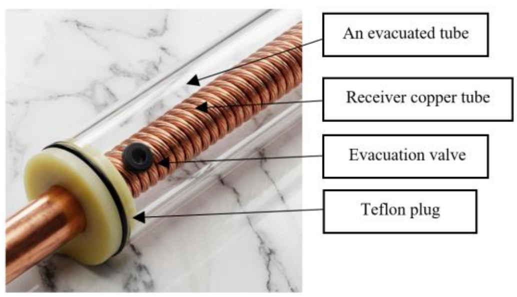
Item	Value
Channel aperture width	25 cm
Channel length	100 cm
Focal length	3.91cm
Linear diameter	33.32 cm
Channel depth	10 cm
Total aperture area of	490.87 cm^2
channel	2454.37 cm^3
The volume of channel	72.6°
Rim angle	5.7
The concentration ratio	

Table 2. Specification properties of SPTC

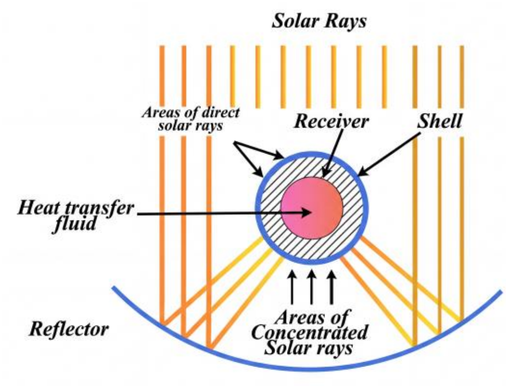
Part	Type of material
Receiver tube	Copper
Mirror	Stainless steel 304
Receiver tube shell	Glass

3.2 Receiver tube design

The corrugated copper tube functions as a receiver through which the working fluid flows, and it absorbs solar radiation reflected from the parabolic mirror to facilitate thermal energy transfer. The receiver tube is positioned along the focal line of the parabolic channel to ensure optimal concentration of the reflected solar rays, thereby maximizing thermal efficiency. The receiver assembly comprises two primary components: a corrugated copper tube and an outer glass evacuated shell to eliminate the heat loss and air circulation, as depicted in Figure 5.
The receiver tube is positioned in a focal point where all the incident sun rays (sunlight) are concentrated, which is called the collector, as shown in Fig.5-b. This is the function of using the solar parabolic collector. The dimensions of the receiver tube are detailed in Table 3.



(a)



(b)

Figure 5. (a) Photograph of corrugated copper tube, (b) side view of (SPTC)

Table 3. Characteristics of the receiver tube

Item	Value
Length of the copper tube (L)	100 cm
Copper tube outer diameter (do)	1.9 cm
The inner copper tube diameter (di)	1.6 cm
Thickness of copper tube	0.3 cm
The shell glass diameter (D)	5.08 cm

The test section was covered with a glass sheet that protected the test section from dust and cleaning. In spite of its reflection, it has limited optical transmission losses, and it may absorb a limited amount of energy at the glass interface. However, the selected high transmission glass cover minimizes the rig heat losses by minimizing the convective and radiative heat losses, outweighing the optical penalty, causing an enhancement in overall thermal performance.

3.3 Sun tracker system

A single-axis parabolic trough (concentrators) tracking system was developed and implemented using the Arduino Uno platform to optimize solar energy capture throughout the day. The system operates by continuously aligning the collector with the direction of maximum solar irradiance, effectively tracking the point of maximum power. When a decrease in light intensity is detected, the tracking mechanism automatically adjusts the orientation of the collector to maintain optimal alignment with the sun, thereby enhancing the thermal efficiency of the system. The main components of the system are detailed in Table 4.

Table 4. Main Hardware Components Used in the Sun Tracker System

Component name	Specification	Function
Arduino Uno Board	ATmega328P, 14 Digital I/O Pins	Controls the logic and operation of the sun tracker.
L298N Motor Driver Module	Dual H-Bridge DC motor driver, 2A max	Controls the rotation of the motor/actuator.
LM2596 Buck Converter	Input: 4–40V, Output: 1.25–37V, 2A	Regulates voltage for components.
LDR Sensor (Photoresistor)	5 mm, GL5528 type	Detects sunlight direction for tracker control.
High Torque Servo Motor	12V/24V, 380 kg· cm, Robot Servo	Rotates the parabolic trough collector.
Power Supply	12 DC volt	Provides input power to the system.
Jumper Wires	Male-to-female, various lengths.	Connects components electrically.

3.4 Experimental study

The experimental setup begins with a primary water tank connected to a pump, which subsequently feeds water through a flowmeter. The flowmeter is used to regulate the inlet water flow rate into the PTC (concentrator) system to the desired value. The PTC is equipped with two pressure gauges to monitor and assess the pressure drop across the system during data collection. Ten K-type thermocouples are strategically distributed throughout the system, five are installed at the inlet and outlet of the corrugated copper tubes within each channel to measure the fluid temperature, while the remaining five are affixed to the external surface of the tubes to monitor surface temperatures. The flowmeter is calibrated to operate at three distinct volumetric flow rates (3 L/min, 5 L/min, and 7 L/min) in order to analysed the effect of flow rate variation on thermal energy gain and overall system efficiency.

3.5 Thermal and Mathematical Analysis

This section presents the thermal performance evaluation of the Solar Parabolic Trough Collector system (SPTC), including the determination of thermal efficiency, the quantity of heat absorbed by the water, energy balance, governing equation, and the corresponding pressure drop.

3.5.1 SPTC Working Fluid Energy balance

The useful thermal energy Q_u [W] determined by the following thermal energy equation:[22] according to the flowing fluid inlet and outlet temperatures

$$Q_u = mcp(T_o - T_i) \quad (1)$$

Where: Q_u = amount of heat gain in (W)

m = water mass flow rate (kg. s^{-1})

cp= specific heat capacity (J/kg. K)

T_o, T_i = outlet and inlet temperature respectively (K)

3.5.2 Solar collector energy absorption

The amount of solar energy absorbed by the collector is determined by multiplying the beam component of solar radiation ($I_b \left[\frac{W}{m^2}\right]$) with the aperture area ($A_o[m^2]$) of the reflector, as outlined in the following equation: [23,24].

$$Q_s = A_o . I_b \quad (2)$$

3.5.3 Collector thermal efficiency

The thermal efficiency of the collector is defined as the ratio of the useful thermal energy gained to the solar energy absorbed by the collector, as expressed in the following equation:[25]

$$\eta_{th} = \frac{Q_u}{Q_s} \quad (3)$$

3.5.4 Collector receiver tube heat transfer analysis

The useful thermal energy analysis of the collector is based on the convective heat transfer between the absorber tube wall and the working fluid according to the following equation: [22,26]

$$Q_u = hA_i(T_w - T_\infty) \quad (4)$$

Where; A_i = inside tube area

T_∞= flowing water temperature (K)

The system heat transfer coefficient was used to evaluate Nusselt's number according to the following equation

$$N_u = \frac{h . d_i}{k} \quad (5)$$

Where: d_i =tube inside diameter (m)

k= flowing fluid thermal conductivity (W/m.K)

3.5.5 Working fluid hydrodynamic and thermal characteristics

To define the flowing fluid characteristic regime Reynold's number is evaluated, which has the following form:[27]

$$R_e = \frac{\rho\, u\, di}{\mu} \quad (6)$$

Where: ρ= density (kg/m^3)

u = flowing fluid velocity (m. s^{-1})

μ= viscosity (kg/m.s)

$$P_r = \frac{\mu\, C_p}{k} \quad (7)$$

Prandtl's number express the ratio of momentum diffusivity to thermal diffusivity

Nusselt number can be evaluated according to the following equation [28]

$$N_u = 0.023\, {R_e}^{0.8}\, {P_r}^{0.3} \quad (8)$$

3.5.6 Parabolic Trough Collector Geometrical Analysis Design

The parabolic collector design geometries of this work can be evaluated from the following equation where F= is the tube focal distance far from the parabola:

$$F = \frac{w^2}{16.d} \quad (9)$$

W = aperture width (m), and

d = channel diameter

3.6 Measurement Instruments and Data Acquisition System:

Accurate monitoring of the system's thermal and hydraulic parameters was achieved using a set of reliable and calibrated instruments. Temperature data were acquired using K-type thermocouples connected to an Arduino Uno microcontroller. Each thermocouple was interfaced through a signal conditioning module to ensure precise digital conversion and minimize electrical noise. This Arduino-based setup enabled real-time temperature monitoring at multiple points, offering cost-effective and flexible data acquisition.

To monitor the internal pressure within the circulation loop, an analogy pressure gauge was installed. This mechanical device provided direct readings in both bar and psi, allowing for continuous observation of pressure conditions and detection of any significant pressure drops during system operation. The flow rate of the working fluid was measured using a vertical variable area flowmeter (rotameter), which displayed readings in Liters per minute (LPM) and gallons per minute (GPM). The float-based mechanism offered a simple yet effective way to manually track and control the fluid flow, ensuring consistent thermal input and reliable system performance. Table 5 presents the specifications and functions of the measurement instruments used in the experimental setup.

Table 5. Specifications of Measurement Instruments used in the Experimental Setup

Name device	Measurement parameter	Model / Type	Measurement Range	Purpose
Thermocouple+ Arduino Uno	Temperature	K-Type+ Arduino Uno	(0-400) ℃	Measuring fluid and surface temperatures at multiple points.
Pressure gauge	Pressure	Analog (FG brand)	(0-30) bar	Monitoring system pressure and detecting drops or unsafe levels.
Flowmeter	Flow rate	ZYIA Rotameter	(0.2-18) LPM	Measuring and manually adjusting the water flow rate.

3.7 Search work methodology

The search work was conducted on an experimental and mathematical thermal evaluation of a newly designed multistage SPTC. The work methodology follows the following flowchart:

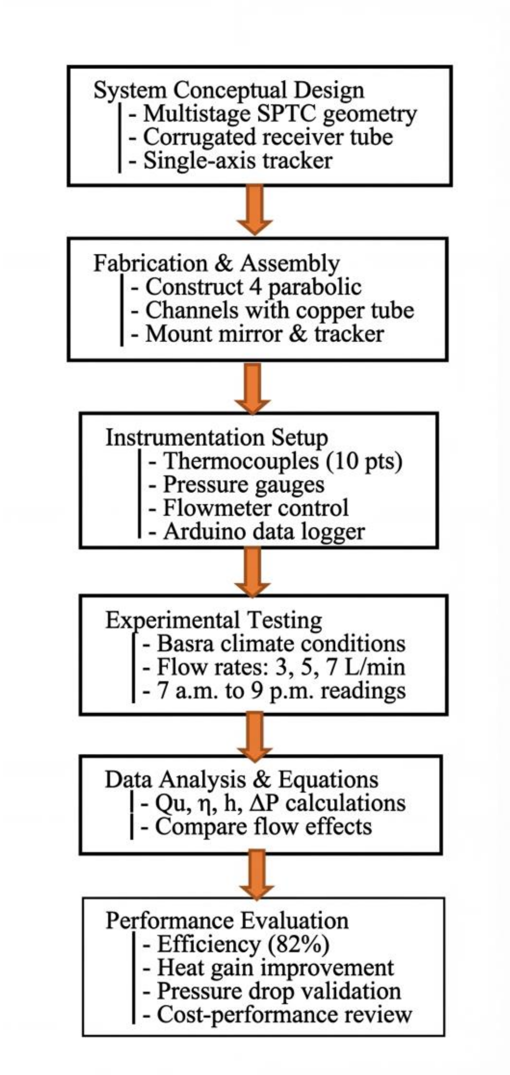


Figure 6: research methodology flowchart

4. Results and discussion

This section presents analysis and experimental results for the solar parabolic trough collector system. The analysis focuses on thermal performance, examining differences in outlet temperature, useful heat gain, and overall efficiency.

The temperature distribution for the novel design of the multistage solar parabolic trough collector (SPTC) is comprehensively presented in Tables 6, 7, and 8, and graphically illustrated in Figures 7, 8, and 9. Corresponding to varying volumetric water flow rates of 3, 5, and 7 L/min, respectively.

Experimental data demonstrated a consistent temperature increase across each channel, confirming the effectiveness of the cumulative heating process for the fluid flowing through the receiver pipe and an increase in solar temperature gain. This increase correlates with a gradual rise in solar irradiance throughout the day, reaching its peak around 2:00 p.m. across all selected flow rates. The observed temperature gain enhancement in the STPC system is attributed to the intensified incident solar radiation as the sun reaches its highest position in the sky, as shown in Figure 10. The observed decrease in the temperature difference between the inlet and outlet of the system with increasing flow rates from 3 L/min to 7 L/min is attributed to the reduced residence time of the fluid within the receiver tube.

The use of a corrugated spiral copper tube as the receiver in the solar parabolic trough collector (SPTC) resulted in an increased heat transfer surface area and turbulence, which consequently enhanced both the thermal energy gain and the outlet temperature of the system. This improvement directly supports the primary objective of the SPTC, which is to maximize the absorption and utilization of solar thermal energy. The experimental results for all investigated water flow rates in the receiver tubes exhibit a bell-shaped distribution, indicating that the heat gain of the absorber is not uniform throughout the day. Heat absorption gradually increases after sunrise, reaches a maximum at midday corresponding to peak solar irradiance, and subsequently declines progressively toward sunset and nighttime.

Table 6 will show the temperature distribution through the SPTC rig for a complete day run at a 3 L/min water flow rate.

Table.6 Temperature distribution at flow rate 3 L/min

Time	T1(°C)	T2 (°C)	T3(°C)	T4(°C)	T5(°C)
07:00 am	25.82	28.01	30.34	32.59	34.85
08:00 am	27.36	30.29	33.25	36.15	39.1
09:00 am	28.21	31.73	35.41	38.92	42.5
10:00 am	30.16	34.3	38.45	42.6	46.75
11:00 am	30.54	35.02	39.65	44.21	48.76
12:00 pm	31.14	35.73	40.32	44.92	49.5
13:00 pm	32.16	36.83	41.52	46.17	50.84
14:00 pm	32.7	37.4	42.27	47.05	51.83
15:00 pm	33.01	37.62	42.19	46.87	51.48
16:00 pm	32.21	36.27	40.35	44.39	48.47
17:00 pm	30.04	33.36	36.68	40.1	43.32
18:00 pm	29.7	31.48	33.25	35.02	36.79
19:00 pm	29.24	30.05	30.84	31.65	32.45
20:00 pm	28.54	29.03	29.5	29.98	30.47
21:00 pm	27.3	27.53	27.8	28.01	28.24

To investigate the effect of increasing the liquid water flow rate and temperature through the SPTC, according to the thermocouples' location, as shown in Figure 4, will be shown in Figure 7.

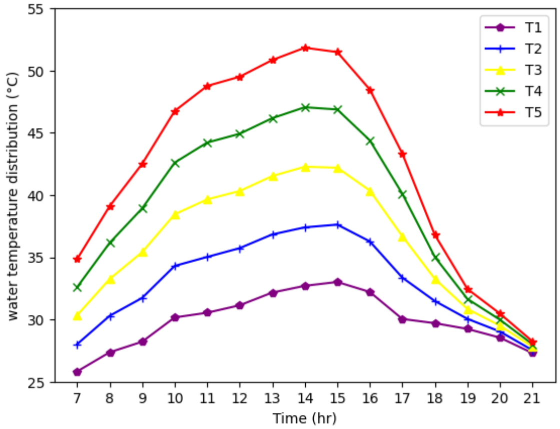


Figure 7. Temperature distribution of water at flow rate 3 L/min

Table 7 will show the temperature distribution through the SPTC rig for a complete day run at 5 L/min water flow rate.

Table.7 Temperature distribution at flow rate 5 L/min

Time	T1(°C)	T2 (°C)	T3(°C)	T4(°C)	T5(°C)
07:00 am	26.01	27.88	29.73	31.58	33.41
08:00 am	27.24	29.83	32.4	34.94	37.52
09:00 am	28.33	31.44	34.52	37.61	40.69
10:00 am	30	33.42	36.83	40.15	43.62
11:00 am	30.5	34.36	37.72	41.45	45.01
12:00 pm	31.3	35.27	38.84	42.71	46.37
13:00 pm	32.43	36.45	40.26	44.1	47.94
14:00 pm	32.52	36.68	40.55	44.57	48.54
15:00 pm	33.46	37.41	41	44.78	48.5
16:00 pm	32.3	35.91	39.28	42.64	46.05
17:00 pm	30.2	33.29	35.89	38.92	41.48
18:00 pm	29.4	31.42	32.5	33.67	34.76
19:00 pm	29.25	30.1	30.74	31.62	32.1
20:00 pm	28.43	29.1	29.41	29.63	29.98
21:00 pm	27.32	27.64	27.83	28.02	28.15

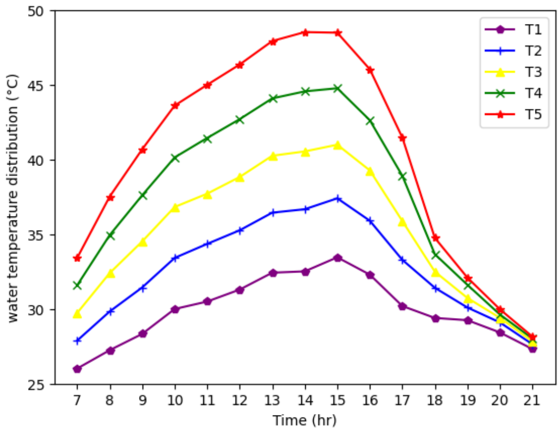


Figure 8. Temperature distribution of water at flow rate 5 L/min

Table 8 will show the temperature distribution through the SPTC rig for a complete day run at 7 L/min water flow rate.

Table.8 Temperature distribution at flow rate 7 L/min

Time	T1(°C)	T2 (°C)	T3(°C)	T4(°C)	T5(°C)
07:00 am	26.2	28.16	29.62	31.19	32.81
08:00 am	27.1	29.35	31.4	33.58	35.67
09:00 am	28.6	31.27	33.79	36.29	38.81
10:00 am	29.1	31.74	34.58	37.42	40.52
11:00 am	30.7	33.95	37.14	40.2	43.28
12:00 pm	31.5	34.82	38.01	41.22	44.41
13:00 pm	32.27	35.64	38.92	42.25	45.5
14:00 pm	32.46	35.81	39.21	42.43	45.71
15:00 pm	33.6	36.95	40.24	43.49	46.72
16:00 pm	32.3	35.3	38.21	41.09	43.94
17:00 pm	30.4	32.91	35.3	37.71	40.1
18:00 pm	29.5	30.62	31.61	32.6	33.64
19:00 pm	29.35	29.98	30.58	31.15	31.72
20:00 pm	28.73	29.08	29.37	29.69	29.94
21:00 pm	28.34	28.52	28.68	28.84	28.97

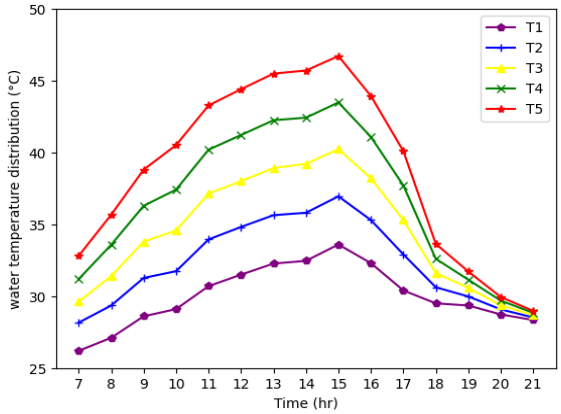


Figure 9. Temperature distribution of water at flow rate 7 L/min

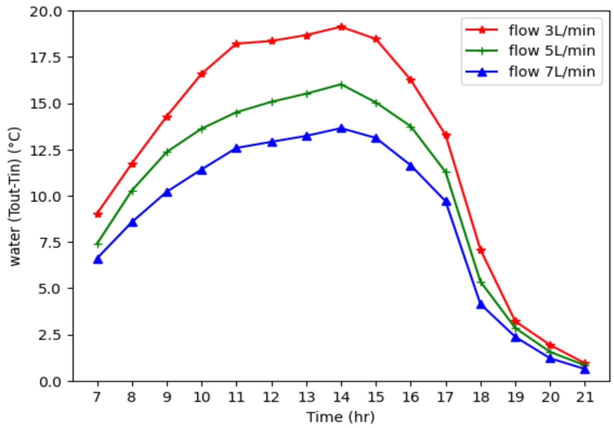


Figure 10. Variation of temperature gain with time at different flow rates

5. The impact of the newly designed (SPTC) on the system's performance variables

The newly engineered design of the solar parabolic trough collector aims to achieve maximum exploitation of the available solar energy by enhancing the system's thermal performance. This is accomplished through the improvement of fundamental operational parameters, most notably, the convective heat transfer coefficient and the thermal efficiency, ultimately contributing to more efficient and sustainable energy conversion within the solar thermal system.

5.1 Heat transfer coefficient

The convective heat transfer coefficient plays a critical role in determining the thermal performance of solar energy collectors. In solar parabolic trough collectors (SPTCs), this parameter reflects the efficiency of heat transfer between the absorber tube surface and the working fluid flowing inside it. A higher convective heat transfer coefficient indicates more effective thermal exchange, which leads to enhanced heat absorption and improved system efficiency. This coefficient is influenced by several factors, including the geometry of the absorber tube, the flow rate of the heat transfer fluid, fluid properties, and the surface condition of the inner tube wall. In advanced SPTC designs, modifications such as using corrugated or spiral tubes can significantly increase turbulence, thereby improving convective heat transfer and overall thermal performance.

Figure 11. illustrates the relationship between the convective heat transfer coefficient and the volumetric water flow rate within the receiver tube of the solar parabolic trough collector (SPTC). The data indicate a clear inverse trend: the heat transfer coefficient decreases as the flow rate increases. The maximum value is observed at the lowest flow rate of 3 L/min, while the minimum is recorded at 7 L/min. This inverse behaviour is primarily attributed to the enhanced thermal residence time and heat exchange efficiency at lower flow rates. At 3 L/min, the working fluid moves more slowly through the receiver, allowing extended contact time with the heated surface and promoting more effective thermal boundary layer development. As a result, the convective heat transfer is maximized. In contrast, at higher flow rates, the fluid passes more rapidly through the receiver, reducing the time available for heat exchange and consequently lowering the heat transfer coefficient.

These findings emphasize the importance of optimizing flow rate in solar thermal systems. Although higher flow rates may increase the total heat removal due to greater fluid throughput, they may also reduce the local heat transfer effectiveness. Therefore, a trade-off must be considered between maximizing energy gain and maintaining high convective heat transfer performance to ensure overall system efficiency.

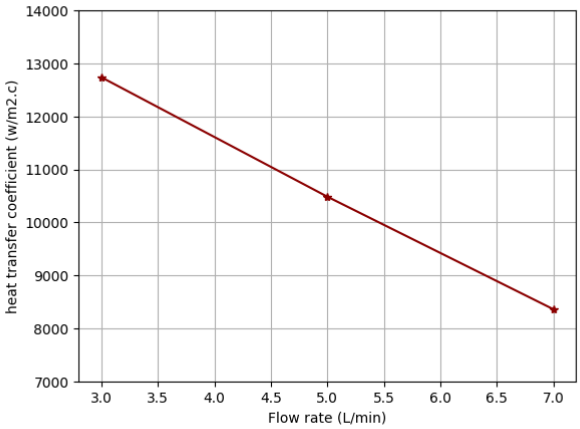


Figure 11. Variation of the heat transfer coefficient as a function of volumetric flow rate

5.2 Thermal efficiency:

Thermal efficiency is the key factor determining the effectiveness of the new solar system design. The thermal efficiency of a solar parabolic trough collector (STPC) is defined as the ratio of useful thermal energy output to the total solar energy input. Key factors influencing efficiency include solar irradiance, the performance of the receiver tube, and the optical efficiency of the mirrors. The receiver tube absorbs and transfers solar energy to the heat transfer fluid (HTF), and any losses in this process reduce overall efficiency.

Figure 12. illustrates the effect of varying water flow rates on the thermal efficiency of the solar parabolic trough collector (SPTC). The data demonstrate a clear and consistent upward trend in thermal efficiency with increasing flow rate. Specifically, the efficiency improves from approximately 50% at a flow rate of 3 L/min to over 80% at 7 L/min, signifying a substantial enhancement in the system's thermal performance under higher flow conditions. This positive correlation can be primarily attributed to the increased heat extraction capacity associated with elevated flow rates. As the volumetric flow rate increases, the mass flow of the working fluid rises, thereby enabling the system to absorb and transport greater quantities of thermal energy away from the

absorber tube. Additionally, higher flow rates contribute to a reduced temperature rise per unit mass, which in turn lowers the temperature differential between the absorber surface and the ambient environment. This reduction in temperature gradient minimizes thermal losses via conduction, convection, and radiation from the receiver, thus enhancing the net thermal efficiency.

Moreover, the increase in flow rate improves the internal convective heat transfer coefficient, facilitating more effective thermal energy exchange between the absorber wall and the fluid. Although this effect was previously associated with a decrease in the local heat transfer coefficient due to reduced residence time (as seen in Figure [9]), the overall system efficiency benefits from the increased thermal energy transport and diminished heat loss mechanisms at higher flow conditions. Increasing the flow rate beyond its optimal point can reduce system efficiency due to higher pumping energy and lower outlet temperatures, potentially limiting downstream heat utilization. Thus, optimization should balance thermal efficiency, temperature gain, and auxiliary energy consumption.

These findings collectively highlight the critical role of flow rate as a governing parameter in the thermohydraulic performance of solar thermal collectors, reinforcing the necessity of carefully engineered operational strategies to achieve maximum efficiency.

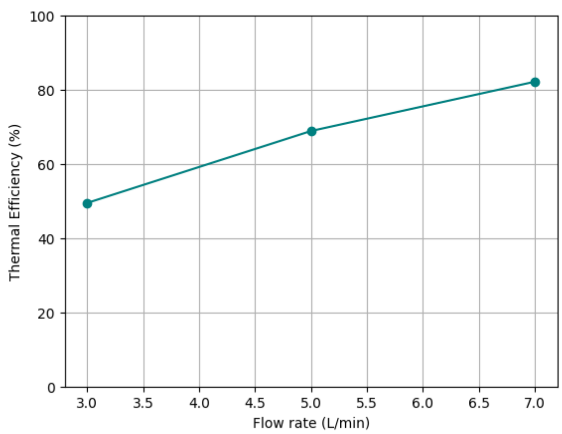


Figure 12. variation of the thermal efficiency as a function of volumetric flow rate

5.3 Pressure drops

Pressure drop is one of the important factors that must be investigated when analyzing the performance of parabolic trough solar energy systems. The pressure drop in a solar parabolic trough collector (SPTC) is mainly caused by frictional losses along the receiver tube and minor losses at connections or bends. Its magnitude depends on fluid properties, flow regime, tube geometry, and operating temperature, which strongly affects viscosity. High-pressure drops increase pumping power demand and reduce net thermal efficiency; thus, accurate estimation and minimization are essential for optimizing SPTC design and operation. Figure 13 illustrates the variation of pressure drop with different volumetric flow rates.

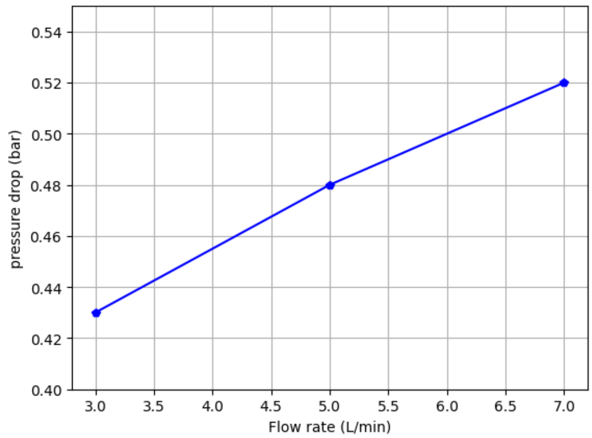


Figure 13. Variation of pressure drop as a function of different volumetric flow rates

5.4 Heat gain

A heat gain of SPTC represents the quantity of useful thermal energy that the working fluid absorbed from the receiver tube due to the incident sun rays. The main variables influencing it are the heat losses, thermal efficiency, and the incident solar irradiation. As the working fluid flows through the absorber tube, the thermal energy is converted into sensible heat, resulting in a noticeable temperature increase. Figure 14. illustrate the correlation between the heat gain and volumetric flow rate of the working fluid (water) within the SPTC. It can be observed that increasing the amount of heat gain is associated with increasing the flow rate from 3 L/min to 7 L/min. This trend illustrates a directly proportional relationship between the flow rate of working fluid and the quantity of heat absorbed by the fluid. The increasing amount of heat gain with the rise of flow rate is due to the improvement of heat exchange, resulting from increased turbulence at higher velocities.

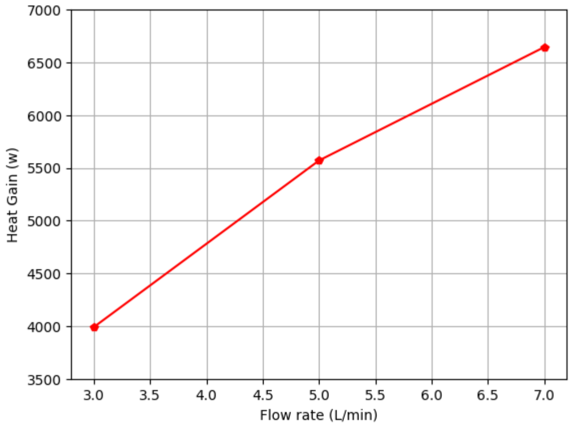


Figure 14. variation of heat gain with volumetric flow rate

5.5 Validation with other works

The experimental findings presented in this study were validated through a comprehensive comparison with previously published literature. The obtained results exhibit agreement with previously reported findings. A detailed comparison was conducted with references Yassen, T A. [30] and Saleh et al. [31], as summarized in Table 9, which showed a high level of agreement.

Table 9. comparison with another study

Parameter	Yassen, T. A. [30]	Saleh.et al. [31]	Presented study
Dimensions	This SPTC consist of one stage or channel, having the following dimensions: PTC length = 1.9 m Aperture width = 1m Aperture Area =1.9 m^2 $D_r$int = 0.026 m $D_r$ext = 0.03 m Focal length =0.25 m	This SPTC consist of one stage or channel, having the following dimensions: PTC length= 1m Aperture width = 0.62 m Aperture area = 0.62 m^2 $D_r$int = 0.011 m $D_r$ext = 0.013 m Focal length = 0.0961 m	This SPTC consist of four channels, each having the following dimensions: Length of channel = 1m Aperture width of channel = 0.25m Aperture area of channel = 0.25 m^2 $D_r$int = 0.016 m $D_r$ext = 0.019 m Focal length = 0.0391m
Type of Enhancement	Receiver tube metal: galvanized steel tube painted black to increase solar absorptivity. Reflector metal: aluminium sheet with shape parabola.	Receiver tube metal: spirally corrugated copper tube. Reflector metal: stainless-steel sheet with shape parabola.	Receiver tube metal: spirally corrugated copper tube. Reflector metal: stainless-steel (304) sheet with shape parabola. Interconnected four channels.
Location	East of Iraq	Central of Iraq	South of Iraq
Key Result	Maximum temperature difference between inlet and outlet of PTC =17 ℃ in lower flow rate. Increasing water mass flow rate increase thermal efficiency.	Maximum temperature difference between inlet and outlet of PTC = 6.4 □ in lower flow rate. Increasing water mass flow rate decrease thermal efficiency.	Maximum temperature difference between inlet and outlet of PTC = 19.13 □ in lower flow rate. Increasing water mass flow rate increase thermal efficiency.
Efficiency	Maximum thermal efficiency reached ≃ 65%.	Maximum thermal efficiency reached ≃ % 51.	Maximum thermal efficiency reached ≃ % 82.
System cost	Not available	Around 450$	850$

6. Conclusion

a novel design of solar parabolic trough collector incorporates several key enhancements, including the following:

- The proposed multistage solar collector offers a cost-effective design by consolidating four individual solar parabolic collectors into a single integrated unit.
- The minimal space required for system construction enhances its applicability in space-limited environments, making it a practical solution for both domestic and industrial applications.
- The use of a corrugated copper tube as the receiver in place of conventional smooth tubing increases the effective heat transfer surface area, thereby enhancing heat exchange performance, and leading to improved heat gain and overall thermal efficiency.
- Applying a corrugated copper receiver tube in an enclosed glass shell enhances the heat transfer, system turbulence, with minimum sun rays' losses.
- The implementation of a corrugated copper tube induces flow turbulence, which significantly enhances convective heat transfer.
- Several parameters were analysed to evaluate the thermal performance of the solar parabolic trough collector (SPTC), including temperature, heat gain, heat transfer coefficient, and solar collector efficiency.
- Utilizing a sun tracking system maximizes the capture of solar radiation, thereby enhancing heat gain and thermal efficiency.
- The novel SPTC improves the temperature gain by approximately 24% with a maximum temperature difference 19oC at 3 L/min compared to single-stage SPTC.
- The new system heat transfer coefficient was enhanced up to 35% while the pressure drop is slightly changed, which indicated the system's hydraulic stability.
- The receiver glass shell introduction minimizes the radiative system losses with a corrugated receiver tube shape to ensure system turbulence that encourages system heat transfer rate.
- The design of multistage SPTC channels was limited by the tracker motor torque and alignment efficiency.
- A cost and thermal performance comparison study with other previous work was done.
- The comparison results show that the new SPTC has a superior thermal investigation performance result with minimum required construction and foundation cost.

Nomenclature

A_i	Surface area
A_o	Aperture area
Cp	Specific heat capacity (J/kg.℃)
CR	Concentration ratio
di	Inner diameter(cm)
do	Outer diameter(cm)
ER	Evacuated receiver
F	Focal distance (m)
GPM	Gallon per minute
h	Heat-transfer coefficient (w/m^2. ℃)
HTF	Heat transfer fluid
I_b	Beam solar radiation (W/ m^2)
k	Thermal conductivity (W/m.℃)
L	Length (m)
LCOE	Level cost of energy
LPG	Liquified Petroleum gas
LPM	Liter per minute
M	Mass flow rate (kg/s)
NER	Non- evacuated tube
Nu	Nusselt number
P	Pressure (bar)
PCM	Phase Change Material
Pr	Prandtl number
PTC	Parabolic Trough Collector

PTCs	Parabolic Trough Collector System
Q	Heat-transfer rate (W)
Q_s	Solar thermal energy (W)
Q_u	Useful thermal energy (W)
R_e	Reynold number
SPTC	Solar Parabolic Trough Collector
T_w	The wall temperature (℃)
$\|T_\infty$	The fluid temperature (℃)
u	Velocity (m/s)
w	Width (m)
Greek letters	
ρ	Density (kg/ m^3)
η_{th}	Thermal efficiency
μ	Dynamic viscosity (N.s/m^2)

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