Design, fabrication and thermal analysis of parabolic trough collector

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Abstract. — Parabolic trough collector (PTC) is considered environmentally friendly and one of the green technologies with net-zero emissions. In this study, performance evaluation of a developed solar PTC system is performed by conducting a series of experimentation. The study focuses on the design, development, and thermal evaluation of a PTC prototype, under hot and humid climatic conditions of Islamabad, Pakistan. Thermal efficiency of the solar PTC system is determined and effect of solar irradiance on thermal efficiency and heat gain is evaluated. Energy and exergy efficiency of the PTC systems are determined 66%, and 38%, respectively.

1 Introduction

The energy requirements of the commercial and industrial sectors has drastically increased during the last decades. Most of this energy has been generated via fossil fuel technologies, which has adversely affected the environment, exacerbated global warming, and had a negative impact on human health. Due to the alarming increase in CO_2 and associated greenhouse gas emissions as well as the depletion of fossil fuel reserves, there is intense need to switch toward alternate and green energy resources. Renewable energy resources, such as biomass, solar, wind, hydropower, and tidal energy, are integrated with existing energy infrastructure to cater the demand, with net zero emission [1]. Fossil fuels significantly account for Pakistan's energy mix with a visible impact on its cash strapped economy. Pakistan's geographic location has a promising potentials of utilizing the solar energy[2].

Due to its significant dependence on fossil fuel resources for energy production, Pakistan is currently experiencing a serious energy and economic turmoil. The government's yearly expenditure of over $3.7 billion on fossil fuel imports exacerbates the strain on an already fragile economy. Additionally, the region ranks seventh in terms of vulnerability to climate change, underscoring the urgent need for proactive measures by the government[3].

Pakistan possesses significant potential in utilizing renewable energy from diverse sources to fulfil the growing demand and tackle issues related to energy security. The government has recently focused on solar energy, as demonstrated by the development of a 100MW solar-powered facility in Southern Punjab. However, research into more effective

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and fruitful approaches is gathering momentum, such as the application of solar thermal technologies for heating applications. One of the most notable substitutes in the field of renewable energy is the solar concentrator. The PTC, Linear Fresnel Reflector System (LF), Power Tower or Central Receiver System (CRS), and Dish/Engine System (DE) are the four technologies that are currently being considered for performance enhancement.

This paper will exclusively examine PTC technology, for solar thermal application. Solar PTC plant produces a hot working fluid by harvesting thermal energy from the sun which can be used for various applications, such as solar cooking, solar water heating, and heat integration into various industrial application. Pilot-scale solar PTC system based projects can help demonstrate the technologies for awareness and indigenous development of the technologies consequently reducing the development cost since their integration into hybrid system with existing fossil fuel based technologies can minimize cost and will help in transition from grey to green energy's.

2 Methodology

2.1 PTC Design

The CAD model of the designed solar PTC is given in **Figure *1***, while geometric properties of the parabolic shape are described by the (Eq. 1) [4]:

$$y = \frac{x^2}{4f} \tag{1}$$

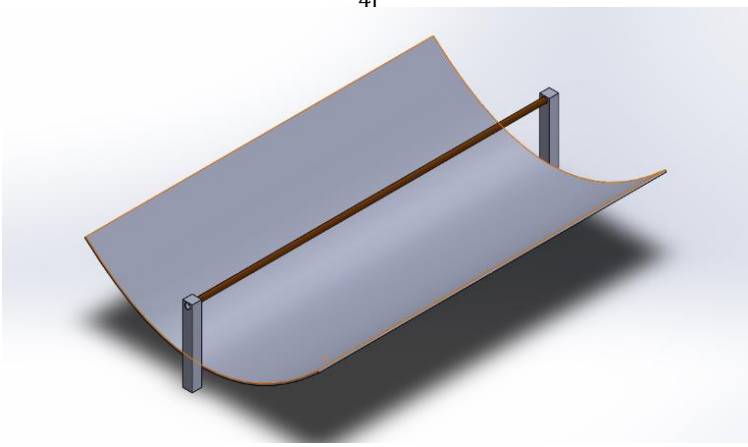


Figure 1 Designed module of solar PTC

The external surface area of the tube is denoted as the absorber area (A_r), and it is determined by developing equation (Eq. 2)[5].

$$A_r = \pi D_r L_r \tag{2}$$

Where D_r represents the diameter of the receiver and L_r represents the length of receiver. The total collector aperture (A_a) is calculated by (Eq. 3) [6].

$$A_a = (w_s - D_r)L_s \tag{3}$$

Where W_s is width of the sheet and L_s is length of sheet.

The concentration ratio (C) is defined as the ratio of the collector aperture area to the receiver area. This ratio is pivotal in increasing the solar irradiance directed onto the energy-absorbing surface. It is calculated by using (Eq. 4). [7]

Where W_s is width of sheet and H_s is height of Solar PTC.

$$C = \frac{A_a}{A_r} \tag{4}$$

Where A_a represents the aperture area and A_r represents the receiver area. The focal distance (f) and rim angle are calculated using (Eq. 5) and (Eq. 6).[8]

$$f = \frac{w_s^2}{16H_s} \tag{5}$$

$$\tan\Psi = \frac{\frac{f}{Ws}}{2\left(\frac{f}{Ws}\right)^2 - \frac{1}{8}} \tag{6}$$

Where f is focal distance and W_s is width of sheet.
The designed Specification of solar PTC are given in **Table 1Table 1**

Table 1 Parameters of PTC

Parameters	**Value**
PTC length (L_s)	1.828 m
PTC width (W_s)	1.22 m
Height of the Solar PTC(H_s)	0.28 m
Reflectivity of PTC	0.85
Aperture Area of the PTC(A_a)	2.2 m^2
Focal length of the PTC(f)	0.33 m
Focal to Diameter Ratio (f/W_s Ratio)	0.27
Rim angle of the dish	85.55°
Receiver length (L_r)	1.98 m
Receiver outer Dia	.03 m
Receiver inner Dia	.025 m
Concentration ratio	13.8

2.2 Schematic of PTC

The schematic diagram of the developed experimental setup based on solar PTC is given in **Figure 2**.PTC is utilized for heating in the experimental setup. The working principal of the solar PTC is to concentrate sunlight to produce heat for thermal applications. The collector's focal line is aligned with an absorber tube, which receives sunlight focused onto its parabolic shape. Within the absorber tube, concentrated irradiance is absorbed by working fluid, which functions as the heat transfer fluid. The fluid gains thermal energy from the concentrated sunlight and its temperature is raised as it passes through the receiver tube. The K-type thermocouple, which has a wide operating temperature range of -270°C to 1260°C, was used to monitor the fluid's inlet and outlet temperatures in the receiver. Hourly measurements were conducted from 09:00 AM to 02:15 PM on various day under direct sunlight at USPCAS-E NUST, H-12 Islamabad. Subsequently, the heated fluid is transferred to a connected storage tank for multiple applications such as space heating, and domestic water heating. Thermal energy storage finds applications in space heating, water heating.

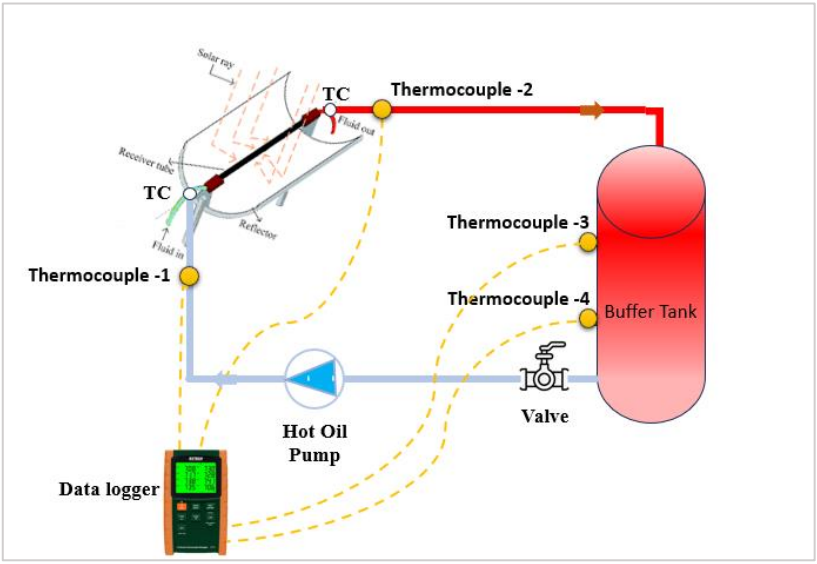


Figure 2 Experimental setup schematic.

2.3 Experimental setup of PTC

Designed PTC consists of reflector material made of Galvanized iron (GI) sheet (22 SWG) with a parabolic shape, an absorber tube made of copper, a support structure and drive mechanism of single. axis tracking with only the tilt angle changing with the direction of the Sun and the other axis remaining fixed, i.e., south Because of their larger concentration ratio and lower absorber surface area, solar PTC are more effective than flat plate collectors. A PTC is constructed using a reflecting material sheet formed into a parabolic shape. The receiving component utilized in this setup features a copper tube with a diameter of 12.7 mm. Copper is chosen for its superior heat transfer efficiency and high thermal conductivity. Developed PTC system is given in **Figure 3**.

Figure 3 Developed PTC Setup for experimental evaluation.

2.4 Parameters of Hot Oil Pump

Hot oil pump for circulation of HTF from the storage tank to PTC. The Specification of pump used is given in **Table *2***

Table 2 Parameters of Hot Oil Pump

Parameters	Value
Volt	220/230
Ampere	5
Phase	Single
R.P.M	1450
H. P	1
cycles	50

2.5 Parameters of Tank

PTC setup comprises of stainless steel (AISI 316) cylindrical tank, which contains 70 liters volume of oil. The oil serves as a medium for circulating heat from the PTC to the tank in a closed loop, allowing it to absorb thermal energy from the PTC. Design parameters of the storage tank is given in below **Table *3***.

Table 3 Design Parameters of storage Tank

Parameters	Value
Height of Tank(H-t)	0.8 m
Diameter of Tank (D-t)	0.381 m
Thickness,	0.01 mm
Porosity	65
Aspect ratio	2.1

2.6 Parameter of HTF

Sunflower oil is used as HTF during the experimentation in this study. Sunflower oil is selected for its favourable thermal conductivity and its suitability for medium temperature applications, ensuring thermal reliability. The density of the HTF is 930.62 kg/m³, and its specific heat is 2115 J/kg*K.

2.7 Thermal Modelling of PTC

As a result of absorbing solar radiation, the temperature of the HTF rises, generating usable energy (Qu). The t useful energy gain, is determined by employing in Eq. (7)[9].

$$Q_u = \dot{m} c_P (T_{out} - T_{in}) \tag{7}$$

Where $\dot{m}$ is mass flow rate of HTF, Cp is specific heat of HTF, T_{out} is outlet temperature and T_{in} is inlet temperature of HTF.
Total absorbed energy is calculated by Eq (8). [10]

$$Q_s = I_a A_a \tag{8}$$

Where I_a is Solar irradiance and A_a is aperture area.
The thermal efficiency of PTC can be expressed using the Eq. (9) [11]

$$\eta_{th} = \frac{Qu}{A_a I_a} \tag{9}$$

Where Q_u is total useful energy gain, A_a is area of aperture and Ia is solar irradiance.

The Exergetic Efficiency of PTC is determined by Eq (10). [12]

$$\eta_{e_x} = \frac{E_{x_u}}{E_{x_s}} \tag{10}$$

Where E_{xu} is exergy flow of the solar irradiation and E_{xs} is instantaneous useful energy flow.

Where the instantaneous useful energy flow of PTC is determined using eq (11). [13]

$$E_{x_s} = Q_s\left[1 - \frac{4}{3}\left(\frac{Ta}{Ts}\right) + \frac{1}{3}\left(\frac{T_a}{Ts}\right)^4\right] \tag{11}$$

Where T_a is Ambient Temperature, T_s is Sun Temperature and Q_s useful energy gain.

Moreover, the exergy flow of the solar irradiation is calculated by employing Eq (12). [13]

$$E_{x_u} = \dot{m}C_P(T_{out} - T_{in}) - \dot{m}C_p T_{am} \ln\frac{T_{out}}{T_{in}} \tag{12}$$

Where Tam and Ts are ambient and sun temperature respectively. In Eq (11), Ts is Sun apparent temperature which is mentioned by Richard Petela [14] taken as 6000K.

3 Results and Discussion

Experiments were carried out on 26th and 28th September 2023 and 4,5 and 11 October 2023 at the US-Pakistan Center for Advanced Studies in Energy (USPCAS-E), at National University of Science and Technology, Islamabad, Pakistan (33°38'32.5" N, 72°59'03.6" E). Multiple parameters were studied such thermal efficiency, heat gain, exergy efficiency keeping mass flow rate of HTF constant at 0.09 Kg/s. The average ambient temperature and Solar irradiance is show in **Table 4**

Table 4 Average Solar irradiance and Ambient Temperature of all test day

Date	**Average Solar irradiation(W/m^2)**	**Average Ambient Temperature (^{O}C)**
26SEP2023	590.29	30.24
28SEP2023	373.90	28.30
4OCT2024	617.84	31.09
5OCT2023	671.01	30.86
11OCT2023	653.70	28.18

3.1 Meteorological Data

This **Figure 4** illustrates meteorological data recorded at the experimental site for different test days, encompassing irradiance and ambient temperature.

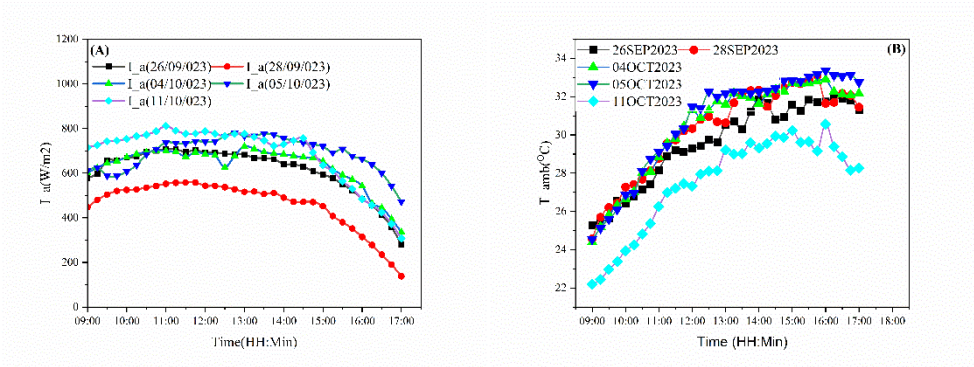
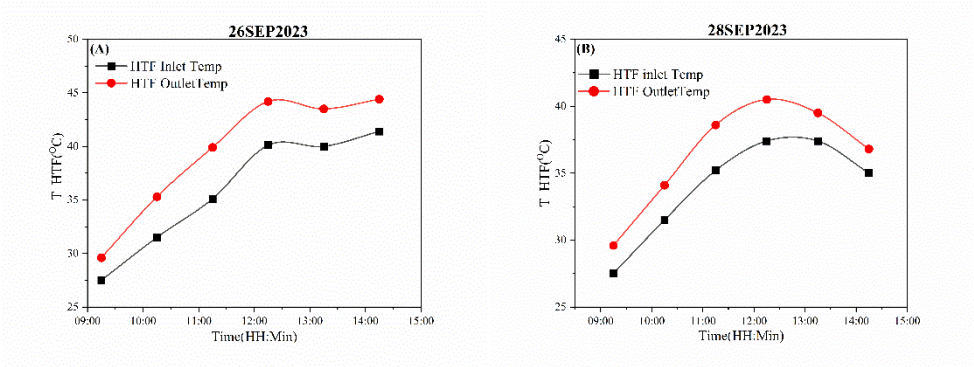


Figure 4

(A)Solar irradiance and (B) Ambient temperature

3.2 HTF Inlet Outlet Temperature of Receiver

The temperatures of the HTF at the inlet and outlet of the receiver are influenced by both solar irradiance and ambient temperature. The variations in the receiver's inlet and outlet temperatures of HTF on of different testing days are given in **Figure *5***.



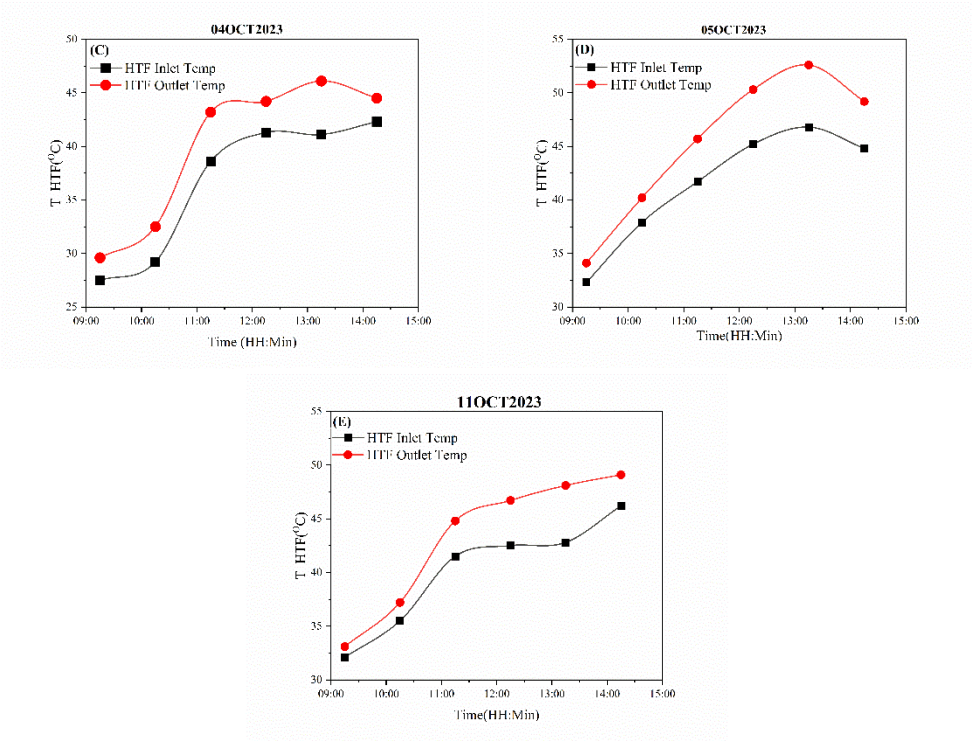


Figure 5

HTF Inlet and Outlet Temperature Variation w.r.t time

Figure 5 illustrates the variation of the HTF inlet and outlet temperatures from the receiver over time. The outlet temperature of the HTF depends on both solar irradiance and ambient temperature, rising with higher levels of both factors. The **Figure *5*** depict the peak outlet temperature from the receiver, recorded at 52.6 ºC at 1:15 pm on October 5, 2023. This occurred on a day with an average ambient temperature of 30.86 ºC and an average solar irradiance of 671.01 W/m^2, marking the highest values observed throughout all experimental days.

3.3 Effect of Solar Irradiance on Thermal efficiency and heat gain

Performance of PTC system evaluated by employing Eq (7) and (9), which incorporates measurements of irradiance as well as the inlet and outlet temperatures of the HTF within the receiver. This assessment is conducted at a specified mass flow rate of 0.09 kg/s. The useful energy gain increases or decreases with solar irradiance variation as it totally depends on solar irradiance. Thermal efficiency and heat gain of experimentation is given in **Figure 6**.

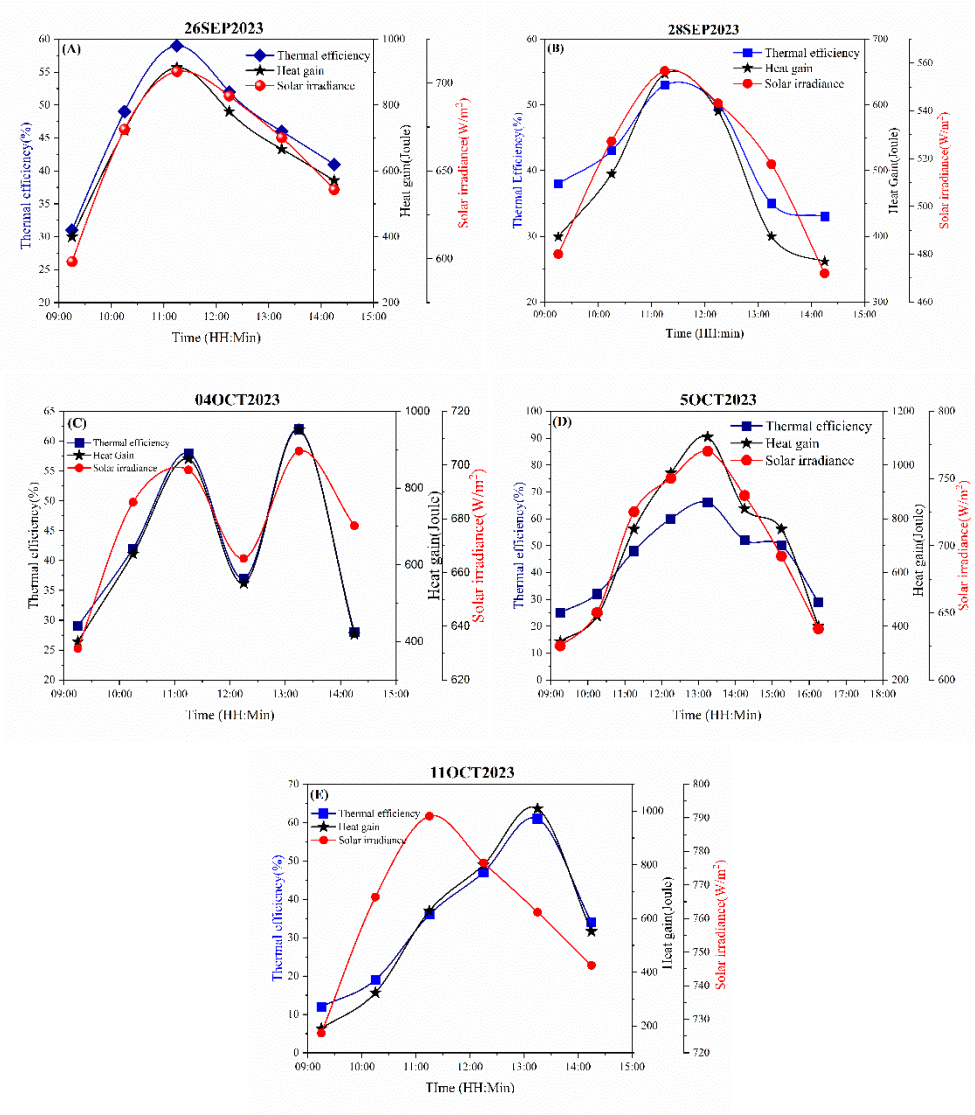


Figure 6

Fluctuation of Thermal efficiency and Heat gain w.r.t Solar irradiance on testing days.

It is evident from **Figure 6** that the variations in thermal efficiency and heat gain with respect to time and irradiance. Thermal efficiency and heat gain exhibit an increasing trend with respect to time. However, a noticeable decline is observed after 02:00 pm, which can be to the reduction in solar irradiance. The highest recorded heat gain and thermal efficiency stand at 1104.3 J and 66 %, respectively, occurring on October 5, 2023, at 1:15 pm. Conversely, the lowest values for heat gain and thermal efficiency, recorded as 190.35 J and 12 %, respectively, are noted on 11th October 2023, at 09:15 am.

3.4 Exergetic efficiency

Under varying solar intensities, the system's exergetic efficiency shows an upward trend with an increase in the HTF inlet temperature. As inlet temperatures drop, energetic efficiency

will eventually approach zero. This is because there are very little boundaries for work output at those stages due to the operating temperatures being close to ambient conditions.Exergetic efficiency of PTC on each testing days is given in **Figure *7***

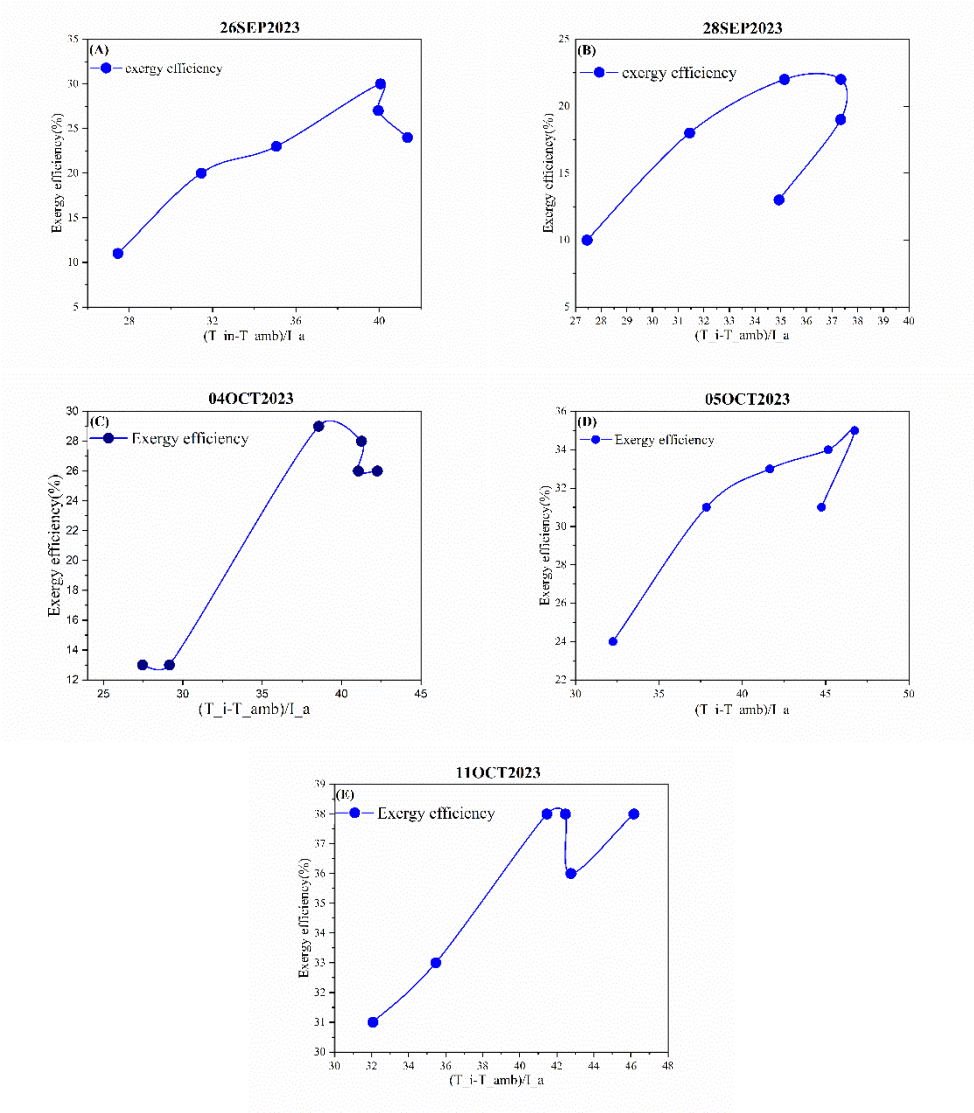


Figure 7

Exergy efficiency of PTC on testing days

It is evident from **Figure *7*** that exergy efficiency rises with an increase in the inlet temperature and decreases with a reduction in irradiance. The **Figure *7*** illustrate the peak exergy efficiency, reaching 38 % at 2:15 pm on 11-10-2023, with an inlet temperature of 46.2 ºC and an average solar irradiance of 653.50 W/m2. Conversely, the lowest recorded exergy efficiency is 10 % at 9:15 am on 28th September 2023, characterized by an inlet temperature of 25.69 ºC and an average solar irradiance of 313.90 W/m2.

3.5 Comparative Analysis

In comparison to the findings outlined in the referenced studies in Table **5**, It is evident from the tabulated data from the literature and this study, the presented method demonstrates competitive results. While Mohamed Chafie et al. reported a maximum efficiency of 60.8%, our method achieves a slightly higher maximum energy efficiency of 66%[15]. Muhammad Faheem et al. showcased varied performance based on orientation, with efficiencies ranging from 48.28% to maximum of 61.66%, however approach adopted in our study provided higher energy efficiency[16]. Additionally, Chafie et al.'s revealed daily energy and exergy efficiencies ranging from 19.7% to 52.6% and 8.51% to 16.34%, respectively, which are notably lower than our attained maximum exergy efficiency of 38%[17]. These comparisons underline the favourable performance of our experimental method, affirming its potential for enhancing the performance and adaptability of PTC system.

Table 5 Comparaison of performance characteristic of PTC system

Ref.	Maximum Energy Efficiency	Maximum Exergy Efficiency
This study	66%	38%
Mohamed Chafie et al.[15]	60.8%	N/A
Muhammad Faheem et al.[16]	61.6%	N/A
Chafie et al. at CRTEn[17]	52.6%	16.34%

4 Conclusion

In this study, a south facing PTC was designed, fabricated, and evaluated under real-world climate conditions of Islamabad, Pakistan.

- Adjusting the incident solar radiation alone can easily increase the system's heat gain and thermal efficiency of PTC.
- Inlet and outlet temperatures of HTF depend on solar irradiance and T_{amb}. Such that both increase with rise in Irradiance and T_{amb}.
- Thermal efficiency rises with rise in heat gain.
- Exergy efficiency primarily depend on inlet temperature also irradiance play a vital role such that when inlet temperature is high, the exergy efficiency also increases while lower irradiance level results in higher exergy efficiency.

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