# Real-time Thermal Performance of a Solar Parabolic Trough Collectors Array with Multiple Receiver Materials under Subtropical Climate Conditions

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## Abstract

Parabolic trough collector (PTC) is the leading solar thermal technology, especially for thermal space heating, and power generation. Such technologies can be a viable solution for energy deficient but solar-rich developing countries like Pakistan. However, the performance of PTCs is significantly influenced by the receiver material under certain climate conditions. Therefore, this work is focused on an extensive experimental investigation with multiple receiver materials of PTCs in the subtropical real climate of Taxila, Pakistan. For that purpose, a total of seven PTCs were connected in series with an aperture area of 8 $m^2$. Aluminum, Copper, and Stainless steel were used for the receivers. The experiments were conducted during May and June. Heat gain and efficiency of the PTCs were examined against three different flow rates of water flowing through the collectors. The maximum recorded magnitude of solar radiations during May and June were 700 W/m2 and 800 W/m2, respectively. The data is collected during a period from 9:00 to 1700 hours. Experimental results revealed that the highest efficiency achieved during June was 32%, 27%, and 22% at 4, 3, and 2 litres per minute (L/min), respectively. The maximum efficiency achieved in June with copper receiver tube was 31% at 2 L/min, 37% at 3 L/min, and 43% at 4 L/min. It is lower for the other two receiver materials compared to copper at the same flow rates. The experimental work has shown good potential for solar thermal applications, such as space heating and small-medium industrial heating processes.

## Keywords

Parabolic Trough Collector System; Absorber Tubes; Receivers; Solar energy. Photothermal conversion

## Introduction

The population of the world is increasing and conventional resources of energy such as oil, gas, and coal are depleting day by day. Scientists have estimated a 50% increase in worldwide energy consumption in 2030 and 70% to 100% in 2050 [1]. Besides polluting the environment, fossil fuels existing in the form of coal, gas, and oil are also diminishing because the dissipation of fossil fuels is perilously rising along with the improvement in the quality of life, industrialization of developing nations, and population growth [2]. The ability of the atmosphere to keep the earth's surface warm is generally known as the greenhouse effect. Carbon dioxide ($CO_2$) and Methane ($CH_4$) gases (greenhouse gases) produced during domestic and industrial activities contribute to the anthropogenic greenhouse effect increasing the earth's surface temperature [3].

Kalogirou [4] showed that if the atmospheric concentration of greenhouse gases continues to rise at the current rate, the temperature of the earth would rise from 2-3 °C in the coming century. According to this forecast, the seawater level is expected to rise by 30-60 cm by the end of the 21st century. The rise in sea level can result in flooding of nearshore accommodations, dispersion of fertile agricultural zones to higher altitudes, and difficulties in the accessibility of irrigation water. Thus, such aftereffects could endanger the continuity of populations.

The depletion of natural reserves, escalated demand for conventional energy, fuel price escalation, and pollutants' level & emissions of greenhouse gases are invigorating the policymakers and the planners to identify renewable/alternative resources of energy like wind power, solar energy, etc [5]. The decentralized energy resource module has been identified as an alternative energy resource that can mitigate the environmental pollutants, greenhouse gases and meet the growing energy demands both in the domestic and commercial sectors.

Renewable energy resources are regenerative and virtually inexhaustible. Renewable energy resources are viable alternatives due to their abundance and cleanliness to overcome fossil fuel depletion and global warming issues. Solar energy is the aged energy source used for a variety of purposes, like domestic and industrial water heating, domestic cooking, and electricity production.

Solar thermal systems for process heat and hot water are reliable and well-proven green sources of energy. Solar energy due to sustainability and exhaustibility attaining worldwide concentration as a viable alternative. According to International Energy Agency (IEA) statistics of 2019, industry consumes 30% of final energy worldwide [6]. In this, 75% is used for industrial heating applications like textile, food, transport equipment, chemical, metal, and plastic treatment. Medium temperature solar collectors are viable options to fulfill industrial heating demand.

Luckily, Pakistan lies in the belts that are rich in solar energy resources where the typical annual solar energy potential is approximately 5.5 kWh/m$^2$/day. Pakistan is located in the fully sun-drenched belt having the geographical coordinates of latitude 24-37$^o$ North and 62-75$^o$ East [7]. The annual availability of approximately 6840–8280 MJ/m$^2$ put Pakistan in the richest country in the context of sun energy potential [8]. Concentrated solar power is the most established and one of the first application areas which were studied [9]–[11] for a temperature range of 300 - 400 °C and the geometrical concentration ratio (CR) was between 20 to 30. For other applications of parabolic trough collectors (PTCs) where the required temperature is between 100 - 250 ℃, the geometrical CR was between 15 and 20. Solar collectors can be used for a variety of applications like solar process heating as these systems have very minute effects on the environment and PTCs be very environment friendly [12]. PTCs have also shown substantial performance elevation when they were tested as retrofits to the concentrated photovoltaics [13]. PTCs have also been tested for seawater desalination as they can provide economical water treatment by efficiently harnessing solar energy [14]. PTCs have also been tested for cooling applications in warm and humid areas and have shown very encouraging results [15].

Many of the studies are focused on various design aspects of PTCs. A study presented a rational design for the structure of PTC by the construction of different models that were better suited for the indigenous facilities with variation in structures, their configuration and material, and methods that are used for manufacturing [16]. In another study, three different design concepts were analysed for the generation of solar steam: 1. unfired boiler concept, 2. the concept of the flash boiler and, 3. direct steam generation [20]. A study highlighted the advantages and disadvantages of concentrated PTCs by comparing them with conventional flat-plate collectors [21]. Similarly, the performance of PTC was investigated with the designed intercept and slope of 0.387 and 0.638, respectively. Moreover, a study presented a design and constructed a model of a two-axis tracking system of the sun. Eventually, it was concluded that the two-axis tracking system collects 46% more solar energy than the fixed one [17].

Furthermore, the performance of a PTC under the climate conditions of Merida and Yucatan according to the ASHRAE 93-1986 standard was studied by using water as a working fluid [18]. The maximum efficiency of the collector was 5.43%. Another work presented a comparative analysis between two receiver types, with and without glass cover for the fiberglass reinforced plastic made prototype PTC with aluminum foil for April and May at Shivaji University [19]. The observed instantaneous efficiency with and without glass lid was 51% and 39%, respectively. Besides, effects of different rim angles were analysed in five PTCs, three were at a rim-angle of 90° while the remaining two were at an angle of 45° [20]. It was observed through optimization of PTC by using different configurations of the receivers that the use of porous disc increases the efficiency of the PTC but reduces the thermal gradient inside the receiver [21]. In design parameters, CR was considered as a critical design parameter defined as the ratio between the aperture area of the collector and the total area of the absorber tube [22], [23]. In another geometry design using fiberglass and polystyrene in the extruded form with a CR of 9.25 and rim angle of 90°, it was concluded that obtained efficiency curve was comparable with the efficiency obtained in the literature with a slope equal to 0.683 and intercept of 0.658 [29].

With technological advancement, by using the technique of hot mirror coatings over the glass cover of the absorber, temperatures up to 700˚C can be achieved [30]. Another study was [24] performed for the evaluation of PTC systems for four different cities of Iran. The results showed that Shiraz city has annual efficiency of 13.91% and 2213 kWh/m$^2$ of useful energy. A study determined the PTC system performance having a linear cubical cavity absorber/receiver using thermal oil as a working fluid. Optical efficiency and thermal efficiency were investigated in Sol Trace software and Maple Software. The maximum heat and thermal efficiency achieved were 618.09 W and 77.26%, respectively for the diameter of the 5 mm tube cavity [32]. Moreover, a work analysed the impact of the pitch to the diameter ratio and roughness height to diameter ratio of corrugated tubes on the thermal and exergy efficiency of PTC. The results indicated that the reduction in pitch ratio and increase in rib-height ratio caused enhancement of thermal and exergy efficiency of PTC [33].

Given the above literature review, it is revealed that many studies were focused on different design aspects of PTCs. However, regional variations in terms of solar radiations, geometry, materials of trough and receivers, and manufacturing skills have a significant influence on the overall performance of PTC systems [25]. Therefore, in the present work, experiments are conducted to evaluate the performance of the PTC array under subtropical conditions and analyze the photothermal performance by varying the material of the receiver tubes as the material of the solar receiver tubes holds substantial significance [26].

**The Parabolic Trough Collector Design**

In the current research work, the system is designed based on a well-established set of equations. The incident solar radiation striking the rim of the PTC makes an angle with the central plane of PTC, called rim angle. The curvature of the parabola is defined by the rim angle. Many possible values of rim angle generate different geometries of parabola while keeping the aperture width constant. Eq. (1), Eq. (2), and Eq. (3) [27] are used to calculate the following parameters:

$$y^2 = 4fx \qquad (1)$$

The radius of PTC aperture width is determined by using Eq. (2).

$$W_{ap} = 4ftan\frac{\delta_r}{2} \qquad (2)$$

The linear width or arc length of the parabola is calculated by using Eq. (3) [13].

$$A_1 = 4f[(sec\frac{\delta_r}{2}tan\frac{\delta_r}{2}) + ln\ (sec\frac{\delta_r}{2}tan\frac{\delta_r}{2})] \qquad (3)$$

CR is a key parameter in the optical analysis of PTC. The efficiency of the PTC directly depends on the CR [32]. Eq. (4) and Eq. (5) are used to calculate the CR and area of receiver $A_r$.

$$CR = \frac{A_{ap}}{A_r} \qquad (4)$$

$$A_r = \pi d_0 l \qquad (5)$$

Thermal efficiency is the basic parameter for judging the performance of any thermal system and hence for the performance of solar thermal collector system [28]. Theoretical effective heat gain from the collector can be obtained by using Eq. (6) [6].

$$Q_u = FRA_{ap}[DNI - \frac{A_r}{A_{ap}}U_L(T_{in} - T_a)] \qquad (6)$$

The input energy i.e., available solar irradiation at the aperture was calculated by using Eq. (7) [30].

$$Q_S = A_a.G_b \qquad (7)$$

Experimental useful heat gain from the collector can be expressed by using Eq. (8).

$$Q_u = \dot{m}.C_p(T_{out} - T_{in}) \qquad (8)$$

The experimental thermal efficiency of the PTC was obtained by using the Eq. (9) [29], [30].

$$\eta_{exp} = \frac{\dot{m}.C_p(T_{out}-T_{in})}{DNI.A_{ap}} \qquad (9)$$

**Experimental Setup and Measurement Procedure**

In the current work, locally available materials are used for fabricating the experimental setup. In the setup, parabolic troughs are placed which concentrate the incident solar radiations on the focal line where absorber tubes (receivers) are placed. These concentric solar radiations when falls on the absorber tube transferred solar energy to the fluid that flows inside these tubes. In this way, this solar energy is converted into thermal energy. The design specifications of PTC that are used in this study are given in **Table 1**. The schematic illustration of the PTC system is presented in **Figure 1 (a)**.

Experimental setup of current research consists of the supporting structure of PTC which contains parabolic profile curves, galvanized iron (GI) pipe struts, foundation columns, and absorber supporting plate as shown in **Figure 1 (b)**. The material selected for the reflector sheet is Austenitic Polished Stainless Steel (SS) which is non-magnetic. This type of SS sheet is chosen because of its high formability, higher weldability, lower price rates, and easy availability. The reflector sheet has been given a parabolic shape with the help of parabolic profile curves and it lies on mild stell (MS) pipe struts for further support. The reflective material on the concentrating solar thermal collector functions to receive the solar radiations and reflect and concentrate them on the receiver where they transfer their heat to the absorber. It requires a higher specular reflecting surface to reflect maximum possible solar radiations on the receiver [31]. The absorber is a major component of the PTC system. The incoming sunlight radiations are converted to heat by the absorber and heat is transferred to the heat transfer fluid (HTF) flowing through the absorber. An anti-reflective glass cover can be used to minimize the heat losses at higher temperatures [32]. Several selective coatings can also be applied to the receiver to enable it to absorb maximum solar radiation. The coating material must have high absorbance for solar radiations, higher transmittance long waves solar radiations, and low emittance values. The materials used as selective coatings are usually metallic oxides. Black chrome coatings have widely used for solar thermal collectors. In this present study, black chrome coating is applied on the material as an absorptive coating as shown in **Figure 1 (c)**. A storage tank is also placed at the outlet of PTCs. The solar tracking was a uniaxial manual. A pump is used to drive the HTF from the feed tank.

**Table 1 -** Design specifications of each PTC.

| Specification | Symbol | Dimension |
|---|---|---|
| Aperture Width (m) | *Wap* | 2.65 |
| Length (m) | L | 2.792 |
| Depth of Parabola (m) | h | 0.663 |
| Focal Length (m) | *f* | 0.663 |
| Aperture Area ($m^2$) | $A_{ap}$ | 8 |
| Rim Angle (˚) | $\varphi_r$ | 90 |
| Concentration Ratio | *CR* | 33 |
| Receiver outer diameter ($m^2$) | $D_o$ | 0.025 |
| Receiver Inner diameter ($m^2$) | $D_i$ | 0.022 |

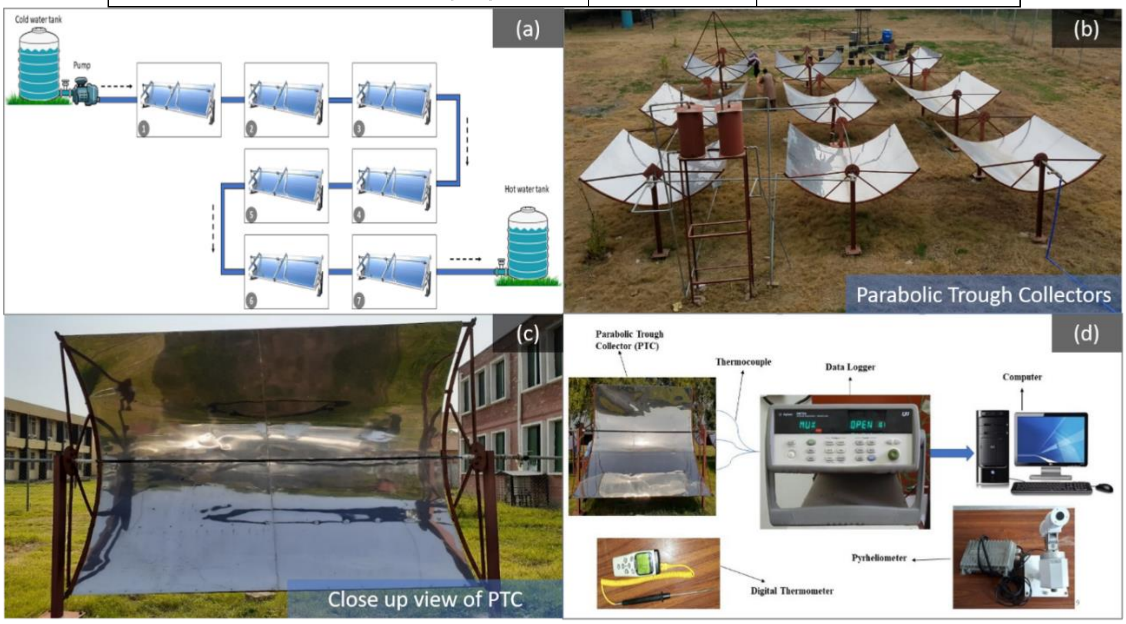


**Figure 1.** Schematic illustration of collectors' configuration (a), experimental setup (b), close view of PTCs (c), and instruments used during experimentation (d).

In this study, thermal performance of PTC by using water is experimentally carried out under real subtropical conditions of Taxila, Pakistan (Latitude 33.7458 N, Longitude 72.7875 E) during different days of May and June for time 9:00 to 17:00 hours.

Experimentation is performed at three different water flow rates at 2, 3, and 4 litres per minute (L/min). The ambient temperature is measured with the help of a digital thermometer. Inlet and outlet temperatures of heat transfer fluid are recorded with the help of thermocouples attached at the inlet and outlet of each PTC's receiver/absorber. Operating water temperatures are measured by using K-type thermocouples with a sensitivity of 0.01°C. Thermocouples are attached to the data acquisition system for continuous data recording. Wind Speed was also measured at every interval of 15 minutes with the help of an anemometer. Solar radiations are recorded by using a pyranometer (model TBS-2-2 with a spectral range of 280–3000 nm and sensitivity of 9.876 μV/Wm−2). A flow meter was placed between the PTC and pump to obtain the mass flow rate. **Figure 1 (d)** shows all the instruments used in experimentation.

## Results and Discussion

In the current work, experimentation is performed under real conditions of the subtropical climate of Taxila, Pakistan for the extreme summer months of May and June. Key parameters varied include water mass flow rate and multiple receiver materials. The results are presented in terms of temperature difference achieved thermal energy gain, and system efficiency.

### Subtropical Climate of Pakistan

Pakistan lies in an area where the sun shines approximately 300 days per year [8]. The average normal direct solar radiation per day in Pakistan is 5.5 kWh/$m^2$ [33]. Pakistan has a maximum potential of solar energy in the areas of south Punjab, Baluchistan, and Sindh. Taxila, Pakistan (Latitude 33.7458 N, Longitude 72.7875 E) also has the potential of solar energy where direct solar radiations reach approximately up to 700 W/$m^2$ in May and 800 W/$m^2$ in June. The months of April, May, June, July, and August are perfect for solar energy harvesting. The direct radiations for summer in Pakistan are shown in **Figure 2 (a)**.

**Figure 2 (b)** shows the variation of local ambient temperature and speed of the wind during the whole experimentation period. An increase in wind speed is observed with time, minimum wind speed is found around 9:00 while the maximum is observed at 17:00. Whereas ambient temperature increases from 9:00 to 12:00 and then trend becomes constant, however, around 14:00 a sudden increase in temperature is observed. The ambient temperature increases constantly from 30.8 ˚C to 35 ˚C. The maximum ambient temperature is recorded at 17:00. While the wind speed varies from time to time, at 09:00 the wind speed is 1.3 m/sec, at 11:00 speed was 2.2 m/sec and at 15:00 the wind speed is maximum that was 2.6 m/sec, while at 17:00 the speed recorded was 1.9 m/sec.

The average solar radiations of all experimental days during the experimentation period are shown in **Figure 2 (c)**. The factors like clouds, humidity, dust, and wind speed in the atmosphere also cause variation in solar intensity. Maximum solar radiation of 800 W/$m^2$ is achieved in June.

Solar radiations that were reflected by the trough onto the receivers are also recorded. The average reflected solar radiations on the receiver are shown in **Figure 2 (d)**. During June maximum radiations are reflected by the reflectors at the receiver. In May, the maximum radiations that incident at the receivers is approximately 2400 W/$m^2$ while minimum radiations observed as 1400 W/$m^2$ at 1700 hour. In June, the maximum radiations that reach the receiver are 2500 W/$m^2$ while the minimum radiations received are 1500 W/$m^2$.

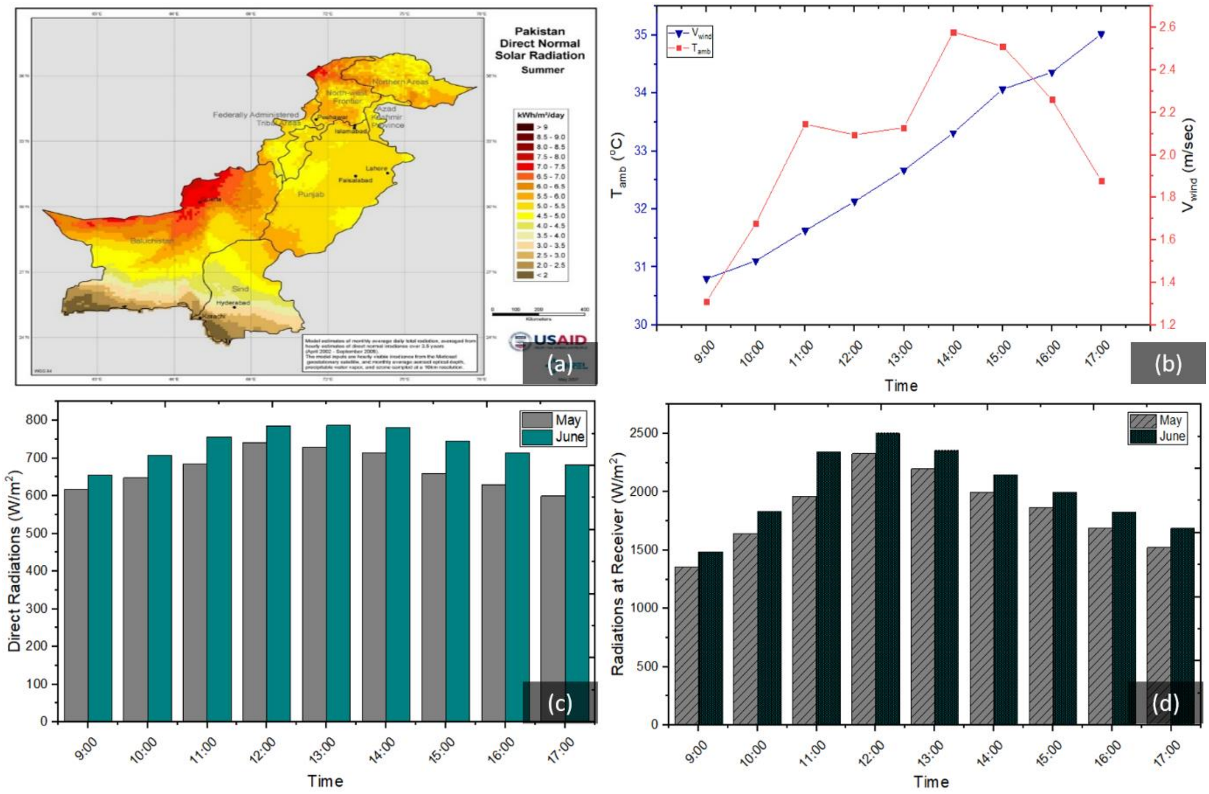


**Figure 2.** Solar Radiation Map-Pakistan with Taxila location [34] (a), average ambient temperature and wind speed (b), average solar radiation during the experimentation (c), Average Reflected Solar radiation on Absorber for all Experimental Days (d).

## Temperature Gain (ΔT) Achieved from PTC Array

The resulted temperature gain (ΔT) is one of the key parameters which is achieved from the PTC system during May and June at different water flow rates. The maximum ΔT is achieved during June at 2 L/min. The temperature difference achieved is approximately 89.5 °C at 12:00 PM during June, while during May ΔT is 70 °C. At 3 L/min the ΔT achieved at 12:00 PM during May and June is 55 °C and 75 °C, respectively. The maximum temperature difference (ΔT) achieved at 4 L/min during May is 45 °C and 67 °C during June.

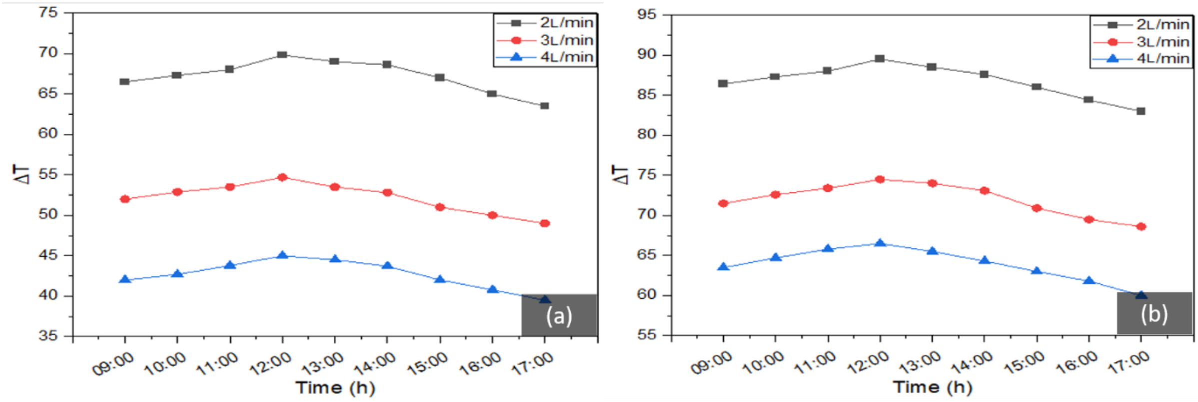


**Figure 3.** Temperature difference in May (a), and June (b).

The average ambient temperature recorded during May is 30 °C at 9:00, at 13:00 was approximately 32 °C while at 16:00 was 33.5 °C, while during June the average ambient temperature recorded was 31.5 °C at 9:00, at 13:00 was 35.5 °C and at 16:00 hour 35 °C was recorded. The recorded ΔT during May and June is given in **Figure 3 (a)** and **Figure 3**

**(b)**, respectively. It can be observed that significant gain in temperature is achieved through the PTC array.

### The System Thermal Efficiency

In the current work, seven PTCs were connected in series to form an array for the experimentation in May and June. The results achieved at different flow rates i.e., 2,3 and 4 L/min through this array during May are shown in **Figure 4 (a)**.

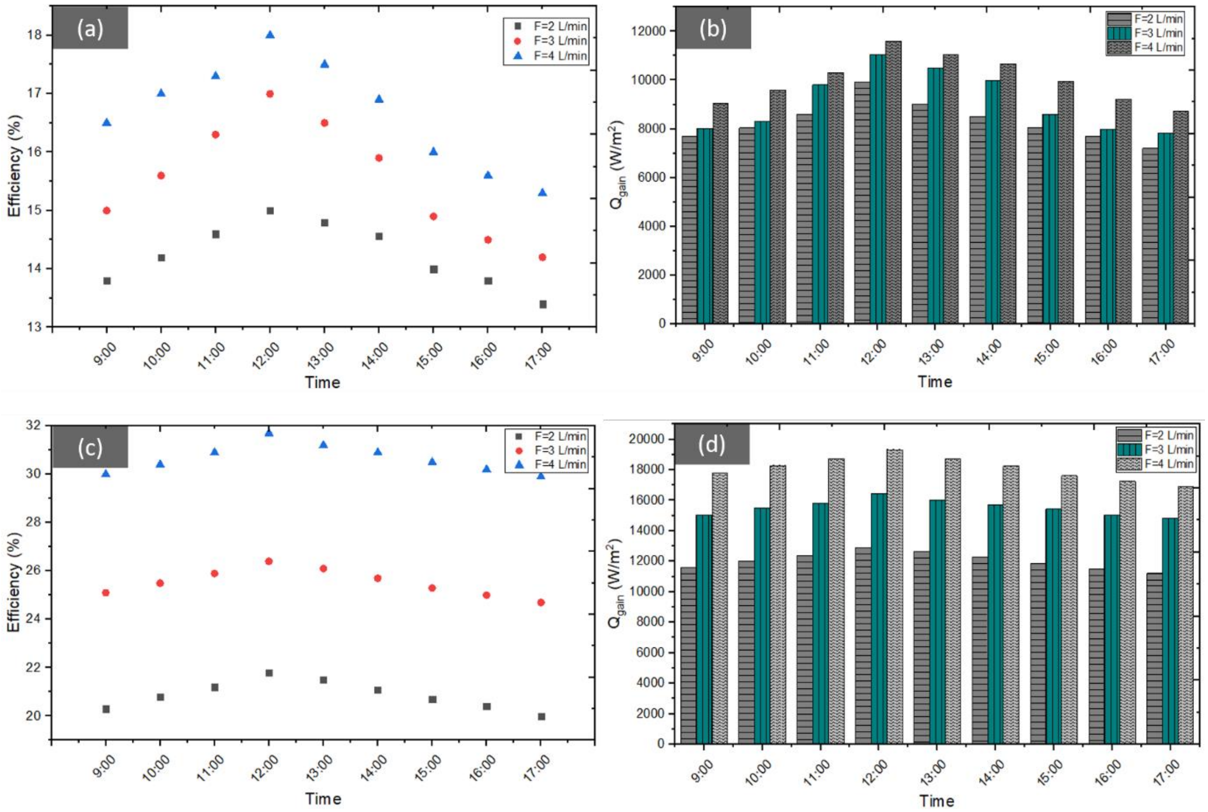


**Figure 4.** Efficiency of PTC System in May (a), heat gained by PTCs system array in May (b), efficiency of PTCs System in June (c), and Heat Gained by PTC System in June (d).

It can be observed that the thermal efficiency of the PTC system array at 2 L/min and 9:00 is approximately 14% and increases due to solar radiation at 12:00 PM as it is 15%, and at 17:00 it is approximately 13.5% due to reduction in radiations. However, when the flow rate is increased up to 4 L/min around 9:00 the observed efficiency is around 16.5%, while at 12:00 PM it was 18% and at 17:00 the efficiency of PTCs was 15%. It can be observed that a high flow rate results in more heat gain which subsequently increases the system efficiency.

Heat gain observed through the PTC array during May is shown in **Figure 4 (b)**. The heat gained by the PTC array at 9:00 at 2 L/min was approximately 7800 W/m$^2$ at 3 L/min heat gained was 8000 W/m$^2$ and at 4 L/min was 9000 W/m$^2$. At 12:00 PM the heat gained 10000 W/m$^2$ at 2 L/min, at 3 L/min 11000 W/m$^2$ while 4 L/min heat gained was approximately 12000 W/m$^2$. While at 17:00 the heat gained at 2 L/min was approximately 6500 W/m$^2$ at 3 L/min 7500 W/m$^2$ and at 4 L/min the heat gained was 8500 W/m$^2$.

Similarly, thermal efficiency and heat gain of the PTC system array during June are shown in **Figure 4 (c)** and **Figure 4 (d)**. It can be observed that the system thermal efficiency achieved is maximum at 4 L/min at 12:00 PM is approximately 32% and the heat gain is also highest at this time due to higher solar radiations compared to other times of the day. It is further to note that the system resulted in performance is much better in June compared to May.

**Effect of Receiver Material**

In the current study, the efficiency of different materials of the receiver is also evaluated. Variation of thermal efficiency with Aluminium, Copper, and Stainless Steel at different flow rates is shown in **Figure 5 (a-c)**. The efficiency achieved at 2 L/min and at 9:00 by Aluminium receiver/absorber is around 17%, for copper, it is 29%, and for Stainless Steel (SS) is 12%. Whereas it increases at 11:00 and 13:00, the efficiency was 20% by Aluminium, 31% by copper, and 14% by Stainless Steel as evident in **Figure 5 (a)**. Topmost efficiency is obtained with copper is 43% at a flow rate of 4 L/min as shown in **Figure 5 (c)**.
The efficiency of Copper is greater than Aluminium and Stainless Steel, the reason is that the thermal conductivity of copper is 411 W/m K, Aluminium is 164 W/m K, and Stainless Steel is 19 W/m K [35]. Due to the high thermal conductivity of copper, the efficiency achieved by copper absorbers/ receivers is higher than aluminium and stainless-steel receivers. While Aluminium has more thermal conductivity than stainless steel so aluminium receivers/absorbers result more efficiently than stainless steel receivers/absorbers.

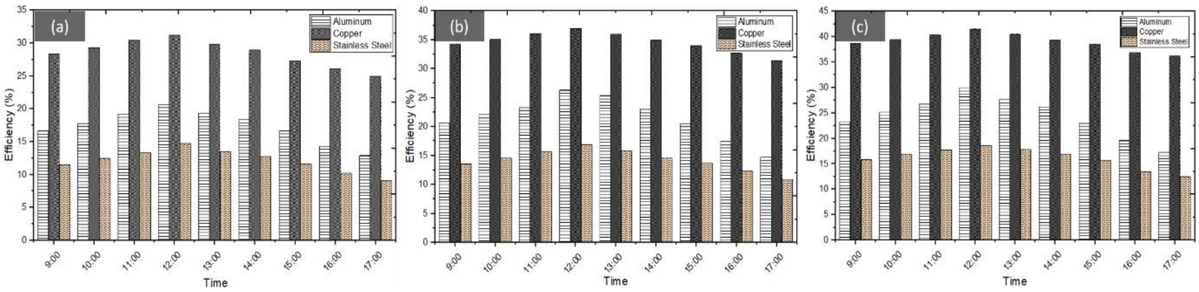


**Figure 5**. Efficiency of Different Material Receivers/Absorbers at 2 L/min (a), efficiency of different material receiver/absorbers at 3 L/min (b), and efficiency of Different Material Receivers/Absorbers at 4 L/min (c).

**Conclusion**

In the current research, an experimental thermal performance of PTC array was evaluated under subtropical climatic conditions of Taxila, Pakistan during May and June. The obtained results showed that during June, there are maximum radiations compared to May. Therefore, the maximum efficiency and heat gain obtained during June. It is observed from the results that the efficiency of PTC depends upon the flow rate of working fluid i.e., at maximum flowrate, maximum efficiency can be achieved. The maximum temperature difference (ΔT) achieved at 4 L/min during May is 45 °C and 67 °C during June. The maximum efficiency achieved by the PTC array during June at 4 L/min is about 32%. Moreover, the system performance with multiple receiver materials is also investigated including Aluminium, Copper, and Stainless Steel. The maximum efficiency is achieved with copper is 43% at flow rate of 4 L/min which is higher than Aluminium and stainless steel due to its higher thermal conductivity.

**NOMENCLATURE**

| | |
|---|---|
| A | Area $m^2$ |
| $C_p$ | Specific Heat, J/kg °C |
| CR | Concentration Ratio |
| D | Absorber's outer diameter, m |
| *f* | Focal Length, m |
| $G_b$ | Global radiations (W/m2) |
| *l* | Collector Length, m |
| $\dot{m}$ | Mass flow rate (kg/s) |
| Q | Heat Transfer, W |
| t | Time, s |
| T | Temperature, °C |
| $U_L$ | Thermal Loss Coefficient, $\frac{W}{m^2 °C}$ |
| $W_{ap}$ | Aperture Width, m |

| | | | | | |
|---|---|---|---|---|---|
| DNI | Direct Normal Irradiance (W/m2) | q” | Heat Flux, $W/m^2$ | $\varphi_r$ | Rim Angle, ° |
| | | $r_r$ | Rim Radius, m | $\eta$ | Efficiency (%) |

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