Solar concentrators to exploit steam energy/Experimental Investigation of Parabolic Trough Solar Concentrator Equipped with Helical Coil Receiver Tube and Directed by Tracking System

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ABSTARCT

Parabolic trough solar concentrators are commonly fixed line focus topologies. In order to enhance their thermal efficiencies, it is necessary to develop them. A modified receiver, constructed of a tube in the form of helical coil, placed on the concentrator focal line and directed by solar tracking system is experimentally investigated in this paper. Experimental thermal performance results for the improved concentrator prototype had been collected for two cases. First case when the system is tested without and with using tracking at constant amount of water mass flow rate and second case when using tracking system for different amounts of water mass flow rates (8, 22.5, 29.4 L/h). The case results, show that the percentage of average increase in terms of solar radiation, outlet temperature of water passing through collector and thermal efficiency of the system combined with tracker were (23, 69, 61%), respectively as compared with non tracking. In second case, it is shown that increasing the flow rate causes decrease in outlet water temperature averagely with (120.8, 63.8, 46.1°C), and maximally with (160.5, 76.4, 50.4°C), respectively. The corresponding values of concentrator thermal efficiency were averagely of (50.3, 49.5 and 44.3%) and maximally of (68.6, 67.4 and 47.8%), respectively.

Keywords: Parabolic trough; solar concentrator; helical coil receiver; thermal efficiency; tracking system; Arduino.

Nomenclature

A_C	aperture area (m^2)
C_p	specific heat capacity (kJ/kg.°C)
D_C	helical coil diameter (mm)
D_g	glass tube diameter (mm)
D_P	pipe diameter of helical coil (mm)
I	solar radiation intensity (W/m^2)
L_C	helical coil length (mm)
L_g	glass tube length (mm)
L_P	pipe length of helical coil (mm)
N	number of measurement readings
N_C	helical coil turns
p_C	helical coil pitch (mm)
Q_U	useful heat gain (Watt)
$Q_{U,ave}$	average useful heat gain (Watt)
t_g	glass tube thickness (mm)
t_P	pipe thickness of helical coil (mm)
T_{amb}	ambient temperature (°C)
T_{inlet}	water inlet temperature (°C)
T_{outlet}	water outlet temperature (°C)
$\dot{m}$	mass flow rate (kg/sec)
ΔH	enthalpy difference (kJ/kg)
ΔT	temperature difference (°C)

Greek symbols

η	thermal efficiency (%)
η_{ave}	average thermal efficiency (%)

Abbreviations

LDR	light dependent resistance
PTSC	parabolic trough solar concentrator

1. Introduction

Solar energy can be exploited by using different techniques and applications. The solar energy could be transferred into thermal energy either by a flat-plate solar collector or a solar concentrator. The Concentrated Solar Power (CSP) systems are proven to be the more efficient, because the solar radiation is absorbed, and then reflected to be concentrated on a smaller area, so as to raise the amount of heat captured to maximum rates. Different technologies of the CSP systems might be available, like: Fresnel Reflectors, Solar

Power Tower, Dish Sterling, and Parabolic Trough Solar Concentrator (PTSC) [1].
To provide elevated temperature with acceptable efficiency, a high performance solar thermal collector is needed. System with low-cost technology and light structure for the application of process heating up 400°C could be achieved by using the PTSC. The PTSC can efficiently generate heat at temperatures ranging from 50-400°C [2]. The PTSC is more suitable for small scale field applications because of their simplicity, ease of manufacturing and higher efficiency for energy collection per unit cost than other collectors' topologies. It is simply consisting of a parabola shaped sheet, mostly is made up of Aluminium, acting as a reflector of the sun rays. The parabolic trough reflects and concentrates the thermal energy obtained from the sun over a metal tube, called as a receiver which appropriately carry a heat transfer fluid (HTF), mounted on the focal length of the trough and this energy accordingly absorbed by the HTF. The receiver might be covered by a glass tube in order to minimize the heat loss by radiation and convection. The fluid flowing through the receiver has been heated by the solar radiation reflected and then flows into storage tanks where it will be stored for further use.
The PTSC is the most commonly studied concentrator in the world. There are several topologies of the PTSCs and their applications had been considered in the literature. Most of the significant researches on the PTSCs such as [3–8] were related to solar receivers constructed in the form of straight tubes. The solar receiver straight tube might be constructed in U shaped to get higher efficiency PTSC system as investigated by [9–11].
Generally, to get further enhancement of the heat transfer rate in the solar thermal systems, the straight tubes should be replaced by helical coiled tubes. The helical coils are an important engineering application of curved tubes [12]. The helical coils are commonly used as heat exchangers and steam generators in power plant because of their higher heat transfer efficiency with respect to straight pipe configurations. Therefore, the flow through a curved pipe caused considerable attention. Some studies such as [13,14] had proved that the helical coiled tubes offer advantageous over straight tubes when utilized in heat transfer applications, because of their compactness, easy manufacture and maintenance, lower installed cost, increased heat and mass transfer coefficients, improved thermal efficiency, and space economy in terms of area per unit volume. Another advantage for using helical coils instead of straight tubes is the decrease in the spread of residence time, permitting helical coil tubes to be used for reducing axial dispersion in tubular reactors. Due these advantages, the helical coil tubes have been used in a wide variety of application fields such as chemical reactors, marine cooling systems, food, air condition and heating systems, cryogenic application, cooling process, power generation, nuclear industry, process plant, heat recovery system, etc.
Generally, the helical coil tubes had some pros and cons, could be summarized as follows:
Pros:
- has better heat transfer characteristics.
- has no-dead zone, utilizes the whole coil surface to exchange heat.
- has a large surface area in limited volume and small floor area.
- has no thermal expansion problems.
- high turbulent flow in helical coil reduces or removes fouling.

Cons:
- difficult to be used in corrosive fluid case.
- difficult to be cleaned in fouling case.
- there will be interfering with fluid flow in the dense packed helical coil case.
- has a little bit complex design.

Many studies had interested to employing the helical coils to enhance the performance of systems integrated into various field applications. An ice storage air-conditioning A/C system using helical heat pipe was experimentally investigated by Fang et al. [15]. The experimental performance results showed that using the helical heat pipe enables the system to stably operate through charging and discharging times. This indicates that this system will be adapted for cooling the storage A/C systems in buildings. Thome et al. [16] had introduced an integral pressurized water nuclear reactor to product a steam using a helical coil steam generator. An experimental study was carried out by Lazova et al. [17] to evaluate the helical coil heat exchanger performance at sub- and supercritical operating conditions for Organic Rankine Cycle ORC applications. Zachár [18] designed a tube-in-tube helical flow distributor to enhance temperature stratification of solar hot water storage tanks operated by helically coiled tube heat exchangers to extract thermal energy more efficiently from the storage tank. Panthalookaran et al. [19] focused on improving the operation of a solar humidification-dehumidification system based on identifying the best physical design parameters for a helical coil dehumidifier. Essalhi et al. [20] had designed a new type of a falling film helical coil condenser used in an absorption machine operating with the couple water/Lithium Bromide (H_2O/LiBr) and delivering a thermal power of 10 kW. Bokisova et al. [21] carried out an experimental work for analyzing the thermal performance of a vertical plastic helical coil in a domestic hot water storage tank application. A molten salt helical coil steam generator was represented by Seubert et al. [22] as an alternative to kettle- or drum-type evaporators which are currently used in commercial-scale solar thermal power plants. A helical flow concentric annulus heat exchanger developed for solar absorption refrigeration purpose was developed by Sonawane et al. [23]. The helical heat exchanger was designed to produce temperature of 130 ^{o}C at pressure of 3atm.

Recently, some researchers have improved the solar receiver in the dish PTSC systems in the form of a helical coil tube to get more increase in the heat and mass transfer coefficients and enhance the system thermal efficiency. In these systems, the helical coil is mounted on the focal point of the dish parabola trough. Sagade [24] designed a solar parabolic dish collector with a helical coiled receiver, truncated cone shaped, made up of copper coated by nickel chrome and mounted at the focal point of the dish. The system achieved an instantaneous efficiency of 63.9%. This system could be utilized for heating boiler feed water, laundry applications and other steam generation applications. Sakhare and Kapatkar [25] designed a direct steam generator by non-tracking solar parabolic dish concentrator utilized for heating water and cooking applications. The dish was equipped with helical coil copper tube mounted on its focal point. The experimental results gave an outlet temperature of 215^{o}C and thermal efficiency of 60-70%. Sharma et al. [26] fabricated a parabolic dish equipped with a helical coil receiver manufactured from copper metal positioned at the focal point. The researchers studied the variation of the output temperature with the change in the helical coil geometry. It was shown that the maximum attainable temperature with non-zero pitch helical receiver coated with black paint and capped was approximately 43% higher than that of bare tube helical receiver with zero pitch. MMahale and Virkunwar [27] designed and fabricated a coiled helical copper solar water aclosed air open water cycle by heater with parabolic dish equipped with automatic Global Positioning System (GPS) beacon solar tracking system at conditions of neighbourhood climate to implement higher rates of warm productivity for domestic and small scale industries. Sagade et al. [28] assessed the thermal performance for a parabolic dish water heater equipped with a helical coiled truncated cone receiver coated by black chrome. This collector was utilized for small scale industrial process heat. It produced an instantaneous efficiency with an average of 63% at water flow rate of 0.0056 kg/s. Pavlovic et al. [29] experimentally investigated a simple, low-cost and lightweight structure solar dish collector with a spiral absorber. Water, air and thermal oil were considered as working fluids in different operating conditions. It was found that the maximum value of exergetic efficiency for the thermal oil was 7.58% at inlet temperature of 155 °C.

In the present study, the parabolic trough solar collector system has been improved with some innovative properties. The coiled helical tube used in the dish concentrator has been modified in such a way to be compatible with the designed parabolic solar collector and mounted on the parabola focal length of the trough. The main objective of the present work is to investigate a parabolic trough solar collector prototype provided with a helical coiled tube receiver and directed by an automatic two-axis solar tracking system. This concentrator could be utilized for heating water as well as steam generation for small scale applications.

2. Implementation of the PTSC system

The proposed PTSC prototype system is consisting of five major subsystems: parabolic reflectors (mirrors), receiver tube, metal support structure, working fluid circulation system, and closed loop solar tracking system.

2.1 The parabolic through reflector

The parabolic trough reflector is employed as a solar concentrator to increase the efficiency of the PTSC system. The reflector could be formed by bending a stainless steel mirror image sheet of a highly reflective surface into a parabolic shape. When the parabola surface is directed to the sun rays, parallel rays will fall on the reflector surface and reflected on to the receiver tube. The solar concentrated radiation reaching the receiver will heat the fluid circulating through it, and then transforming it into useful heat. The reflector was designed according to a Parabola Calculator v.2.1 specifications were theoretically calculated and listed as in Table 1. The trough has a focal length of 0.25m from the vertex. The aperture width of the reflector is 1m. The parabolic equation of the designed reflector would be $x^2= 4.16y$. The designed reflector has length of 175.5cm. This length is depending on the length of the frame that is assigned to fix the reflector which approximately equals the length of the helical receiver tube. The parabolic trough is designed with a rim angle of 90°. This angle is chosen on the basis of focal length equal to the height of the parabola.

The reflector had been manufactured using materials with low cost, light and strong structure, and easy to construct. In order to minimize the construction costs, a commercially available stainless steel sheet, with dimensions of (1755mm length × 1000mm width × 1mm thickness) had been used. The stainless steel is characterized by high ability to reflect and concentrates the largest amount of sun radiation, falling on the focus line of the parabolic trough. The steel sheet was mounted longitudinally on a structure frame; which in turn determines the PTSC size as shown in Fig. 1.

2.2 The helical coiled receiver

The traditional PTSC system has been improved by using a modified solar receiver, constructed in the form of coiled helical tube mounted on the focal line of the concentrator trough.

Coiled tubes are mainly used in heat exchanger application because of the presence of secondary flow [30] which considerably enhances heat transfer due to mixing of fluid flowing through the curved tubes. The intensity of secondary flow generated in the helical tube is a function of coil pipe diameter and coil tube diameter. Fig. 2 shows a cut-away view sketch of the helical coil tube. The helical coil was manufactured using bending process to a copper pipe with length L_P, diameter D_P, and thickness t_P. The coil has dimensions of a length L_C, which is approximately equal to the length of the collector, diameter D_C, and pitch p_C. The coil pitch may be defined as the spacing between consecutive coil turns (measured from the centre to centre), adjusted here with $p_C = 1.8\ D_P$. The helical coil tube had been inserted in a smooth glass tube with L_g length, t_g thickness, and D_g diameter. The following analysis considers the dimensional and graphics program, and its operating parameters needed to construct the required coiled tube, which are listed in Table 1.

The coil pipe length L_P could be determined according to Eq. 1 [31]. Initially, this length is needed to form a helical coil with turns of N_C = 116, a diameter of D_C = 41mm, and an average pitch p_C of approximately 10 mm as initial values:

$$L_P = N_C \sqrt{(\pi D_C)^2 + p_C{}^2} \qquad (1)$$

So, $L_P = 116\sqrt{(41\pi)^2 + 10^2} = 1498.6mm \sim 15m$

A copper pipe had been procured from the native markets of Baghdad city, has dimensions with length L_P of 15.24 m, diameter D_P of 6.35mm, and thickness t_P of 0.61mm, could be used to form a helical coiled tube, with length L_C of 1835 mm depending on the length of the collector, number of coil turns N_C of 116, mean coil diameter D_C of 41mm, by using bending process with a pitch coil of p_C. The average value of the coil pitch can be recalculated according to the available pipe specifications. So, Eq. 1 could be rewritten as follows:

$$p_C = \sqrt{\left(\frac{L_P}{N_C}\right)^2 - (\pi D_C)^2} = \sqrt{\left(\frac{15000}{116}\right)^2 - (41\pi)^2} = 11.42\ mm$$

Copper metal was selected for designing the coiled receiver due to its high thermal conductivity of (k=401W/mK). Two metal pieces were fixed by welding at the two ends of the coil pipe to expand its diameter in order to link the coil tube with a pipeline which is connected to a tank used for storing hot water. To increase the absorptive of the receiver, the helical coil is covered with a thin coat of heat resistant black colour paint with an absorption coefficient near 0.9 and is located in the focal zone of the parabola, so as to improve the overall efficiency of the system. To minimize the heat losses of the PTSC, a non-evacuated glass tube with absorptance more than 92% was used to cover the absorber coiled tube. The glass tube with length of 1830 mm, diameter of 58mm, thickness of 1 mm, had been chosen to be combatable with the PTSC dimensions. All the receiver specifications are listed in Table 1.

2.3 Solar tracking system

Because the parabolic trough will reflect only direct-beam sunlight, so it is very necessary to use the solar tracking technique. The solar tracking is one of the most important factors that lead to enhance the efficiency of solar systems, which makes solar radiation perpendicular to the collector and thus obtaining the greatest possible intensity of falling solar radiation, and as a result, elevating the amount of solar energy received by the solar collectors, resulting higher output power. In general, the solar tracking could be represented by two modes: one-axis tracking and two-axis tracking [32]. In the one-axis tracking of the PTSC system, the collector could be orientated in the north-south direction to track the sun from the east to west, while in the two-axis tracking system, the collector follows both of the sun's changing altitude and azimuth, so as to focus parallel solar rays falling on the reflectors right onto the receiver tube. Some researches in the literature had been used a single-axis tracking system to keep the parabolic trough facing the sun [33–35] and some others used a two-axis tracking system [36–38].

The tracking mechanism must be reliable and capable to follow the sun with a certain degree of accuracy, which is depending on the angle of acceptance of the collector, and also execute another job such as returning the collector to its original position at the end of the day or at night and sun tracking the sun during intermittent cloud cover periods.

In this paper, the trough concentrator mounted on a solar closed loop tracker with two axes is used as a key factor to enhance the system efficiency. The solar tracking system is divided into mechanical system and electrical system. The mechanical system includes a main structure that supports the reflector, providing two degrees of freedom (the movement in two directions). A lightweight steel structure was built to provide strong mechanical support against high wind speed and harsh environmental conditions. The mechanical system consists of fixed part and moving part. The fixed part is very important to fix the PTSC system, called the base. The moving part accomplishes two actions: (1) axial motion to move the PTSC from east to west to track the sun rays. This movement might be done by using 12V, 0.4A DC gear box as shown in Fig. (3a), and (2) tilting motion to move the PTSC upward and downward. This movement can be directed by using a 12V, 1.2A linear DC motor to produce a linear movement as shown in Fig. (3b). The electrical part of the tracking system is mainly consisting of an Arduino UNO controller, four light dependent resistances (LDRs), DC power supply, two DC motors, DC water pump, and four channels relay circuit to switch the DC motors used for directing the solar tracking process or to shut down the process. The LDRs will be used as solar sensors for the closed-loop tracking to sense the radiation of the sun and track its movement in order to make solar radiation perpendicular to the collector, and guarantee fall the maximum sunrays on it. This noticeably, raises the amount of light energy captured and then transferred into heat energy. When sun rays hits the LDR, its resistance will decrease. The output voltages of the four LDRs are varied according to the intensity of radiation falling on each LDR. By using this property, the LDRs can detect the solar irradiance from up, down, left and right side. The voltage variation between the LDRs is then converted into input signals to the control circuit. The control circuit converts these signals to the specified motors via the relay circuit. These motors, in turn, adjust the position of the PTSC when maximum solar radiation intensity is received at its aperture. To do this, the sensors need to be mounted on a plastic base in the same plane as the collector and separated by four walls to block the LDRs from the sun when the incoming sunlight is not perpendicular to the solar concentrator. The PTSC system directed by the tracking system is controlled by an Arduino UNO controller board. The Arduino UNO is a single board, includes an electronic circuit open source with an ATmega328P microcontroller, programmed by a computer. The Arduino takes analogue input from the LDRs and enables the DC motors to be fed with electric power via 12V DC battery power supply. According to the location of the sun, the Arduino controller analyses the signals coming from the LDRs. Four channel 5V relay Module 10A circuit board is used to run the DC motors via connecting this circuit between the Arduino and the motors as shown in Fig. 4. The relay circuit receives the electrical signals coming from the Arduino; its work is depending on software loaded into the Arduino microcontroller. To supply the DC motors and the water DC pump in the PTSC system with the required electric power, a 12V 13W solar photovoltaic PV panel, 12V 14Ah Sealed Lead Acid battery, and 12V charge controller should be used.

3. Experimental Setup and Concentrator Testing

The designed PTSC had been constructed and prepared for carrying out the performance evaluation tests under the climate conditions of Baghdad city. The testing area and the experimental setup are shown as in Fig. 1. The experimental tests were carried out with an open loop water flow system for two cases. In the first case, the PTSC was tested without and with using tracking system at constant water mass flow rate of 8 L/h and in the second case, the PTSC is directed by tracking system and tested at different values of water mass flow rates of (8, 22.5 and 29.4 L/h) for three different days on the (17th, 21st and 22th) of April 2020, respectively.

A storage water tank of 20 litres capacity was mounted at a level of 0.5m over the PTSC level to maintain natural flow of water through the collector. Some parameters had been recorded, such as intensity of solar radiation I, ambient temperature T_{amb}, water inlet temperature T_{inlet}, water outlet temperature T_{outlet}, and wind speed. A TES-1333R Data logging solar power meter, placed at the same level of the collector aperture, was used for measuring the sun radiation intensity within the range of (0-2500W/m^2), resolution of 0.1W/m² and accuracy of ±10W/m². A K type thermometer, BTM-4208SD temperature recorder with resolution of 0.1°C/1°C and accuracy of ±(0.4%+1°C) had been used to measure the temperatures, simultaneously, at three different points; ambient, water inlet and water outlet. The ambient temperature could be measured by putting the thermocouple sensor at the surroundings. The temperatures of the inlet water and outlet water had been measured and recorded each time interval of 60 min during the sunshine hours of the day. A Thermo Anemometer with accuracy of ±4% m/s, resolution of 0.1m/s, and ranged with (0.7-42m/s) was placed parallel with the system surface so as to measure the wind speed. To measure the mass flow rate of the water coming from the tank and passing through the collector, a ZYIA Rotameter water flow meter, LZM-4T type with range (100-500 mL/min) accuracy of ±4% was used. Table 3 lists all the specifications of the measuring devices used during the experimental tests. The DC motion motors as well as the DC circulating water pump were supplied with the required electric power from a 12V 14Ah Sealed Lead Acid battery, charged by a suitable 12V 13W solar PV panel and stabilized across 12V charge controller. The DC motion motors are programmed to move for a time of 2sec after each stop of 15min during the daily work period, while the water pump works continuously during the daylight to circulate water through the collector at a given mass flow rate. The experimental setup was implemented and the tests were carried out. The experimental results necessary to evaluate the useful heat gain and the thermal efficiency of the PTSC were collected. The total useful heat gain Q_U and the thermal efficiency η of the PTSC were calculated according to change phase from liquid to steam, at specific time during the time daily experimental tests, as follows [2]:

$$Q_U = \sum Q = Q_{Liquid\ \text{(sensible heat)}} + Q_{\text{Steam (vapor heat)}} \quad (2)$$

, where:

$Q_{sensible\ heat}$: useful heat gain at water temperature < 100 °C

$Q_{vapor\ heat}$: useful heat gain at water temperature > 100 °C

$$Q_{Liquid\ \text{(sensible heat)}} = m^{\cdot}\ C_p\ \Delta T \quad (3)$$

(When the water is still in liquid phase, the output temperature is less than 100°C, C_p= 4200kJ/kg.°C, and ΔT = 100 - T_{outlet}). Where: $m^{\cdot}$ is the water mass flow rate (Kg/sec), C_p is the specific heat (kJ/Kg.°C), ΔT is the difference between the outlet T_{outlet} and inlet T_{inlet} water temperatures (°C).

$$Q_{\text{Steam (vapor heat)}} = m^{\cdot}\ C_p\ \Delta T \quad (4)$$

(When the water is changed into steam phase, the output temperature is more than 100°C, C_p= 2000 kJ/kg.°C, and ΔT = T_{outlet} - 100).

From Eq. 2, the collector useful heat gain Q_U could be rewritten as:

$$Q_U = m^{\cdot}\ C_p\ (T_{outlet} - T_{inlet}) \quad (5)$$

The collector thermal efficiency might be known as the ratio of useful heat gain Q_U during any period of time to the falling solar radiation (A_C I) during the same period. Therefore, the efficiency will be given as:

$$\eta = \frac{m^{\cdot}\ C_p\ (T_{outlet} - T_{inlet})}{A_C\ I} \quad (6)$$

Where, A_C is the aperture area of the collector and I is the intensity of solar radiation.

The average value of the useful heat gain $Q_{U,ave}$ of the PTSC can be calculated as follows:

$$Q_{U,ave} = \frac{\sum Q}{N} \quad (7)$$

Where Q represents the instantaneous useful heat gain and N is the number of readings.

Also, the instantaneous value and the average value of the PTSC thermal efficiency, η and η_{ave}, respectively may be found by the following equations:

$$\eta = \frac{m^{\cdot}\, C_p \int (T_{outlet} - T_{inlet})}{A_C \int I\, dt} \quad (8)$$

$$\eta_{ave} = \frac{\sum \eta}{N} \quad (9)$$

4. Design of the Solar PV Panel

A solar PV panel might be mounted on the PTSC frame in order to capture the entire light incident on it and convert it into electrical energy required for the tracking action. The PV panel was used as an autonomous DC power supply to fed the two DC motors as well as the water pump without the need to any external AC power supply. To stabilizes the PV panel electric output and minimizes any fluctuations in its current and voltage values, a charge controller must be directly connected to the PV panel. This controller charges the battery with DC power to its maximum potential. The PV panel power could be designed depending on the electrical specifications of the motors and water pump used and the working time duration of all motors through the daytime. The test used to design the PV panel was carried on the 26th may 2018, as a longest day during the year. The system working time was specified from the sunrise time at 5:58am to sunset time at 8:18pm. The system uses the two DC motors to move the PTSC system in the X-axis and Y-axis directions, and the DC water pump to recycle the water in the collector. The axes motors were programmed to move for 2sec every quarter of an hour, through the whole working time of the system, while, the water pump was permitted to run continuously during the daytime. Table 2 shows the ratings, the work time and the required electric energy for each motor used in the system. This table, also, demonstrates the calculations necessary for designing the PV panel and thus specifies the required DC battery and charge controller.

The total power of the required PV panel for the proposed design is given by:

$$P_{PV} = \frac{\sum Enegry\ Eequired}{\sum Working\ time} = \frac{143.373\ \text{W.h}}{14.397\ \text{h}} = 9.96\ \text{W}.$$

The value of the required battery energy that is enough to supply the PTSC system with electricity is:

$$E_{Batt} = \frac{\sum Enegry\ Required}{V_{Batt}} = \frac{143.373\ \text{W.h}}{12\text{V}} = 11.95\ \text{A.h}.$$

As a result, a 12V, 13W solar PV panel will be enough to be used for charging a 12V DC 14Ah battery. This will be appropriate for supplying enough electric power to the whole system, without need for external electrical sources. 12V, 10A charge controller could be used to charge and regulate the DC supply battery.

5. Results and Discussion

Some experiments had been carried out under climatic conditions of Baghdad city to investigate the overall thermal performance for the improved solar concentrator prototype. The tests results had been recorded every hour, for two cases. The first case is carried out when the collector is tested without and with using tracking system at water mass flow rate of 8 L/h. The second case, when using tracking system alone for different amounts of water mass flow rates of (8, 22.5 and 29.4 L/h). The system performance results would be compared in the two cases.

5.1. Performance comparison without and with using tracking system at constant mass flow rate:

Two experimental tests had been carried out on the PTSC without and with using the two-axis tracking system, on the days (16^{th} and 17^{th}) of April 2020, respectively, during daytime period from (9 am - 3 pm) at constant water mass flow rate of 8.0 L/h. The results of the performance evaluation tests represented by the solar radiation falling on the PTSC, the water outlet temperature, the useful heat gain, and the thermal efficiency of the system are demonstrated as in Figs. (5-8), respectively. The results of average solar radiation during daylight without and with using the solar tracker are (787 and 969 W/m^2), respectively as shown in Fig. 5, this means an increase in solar radiation by about 23% when using tracking system compared to the fixed system. The increase in the solar radiation will cause an increase in the temperature of the water outlet of the collector as shown in Fig. (6). The outlet water temperature is found to be averagely of (71 and 120 ^oC), respectively, which means an increase by about 69% when using the solar tracker as compared with the fixed system. The corresponding values of the useful heat gain and thermal efficiency of the collector without and with the use of tracking are demonstrated as in Figs. 7 and 8, respectively. The average values of the useful heat gain and thermal efficiency, without and with tracking are found to be (343 and 798W) and (31.1 and 50.3%), respectively. This means an increase in the heat gain and thermal efficiency, averagely by about 132.7% and 61.7%, respectively.

5.2. Effect of water mass flow rate on the PTSC performance

Some experiments had been carried out to investigate the influence of varying the water mass flow rates on the performance of the PTSC equipped with helical coiled tube and directed by two-axis tracking system during daytime period from (9 am - 3 pm). The experimental results were recorded for three different days on (17th, 21st and 22th) of April 2020 and corresponding three different values of water mass flow rate of (8, 22.5 and 29.4 L/h), respectively. The thermal performance was evaluated as shown in Figs. (9-12). These three days almost came within the same climate, and almost under the influence of the same circumstances. Fig. 9 demonstrates the change of the solar radiation intensity during the daylight measured on the chosen three days and at the corresponding three rates of water mass flow. The figure shows that the intensity of solar radiation has average values of about (969, 845 and 941 W/m^2) for the three cases of mass flow rates, respectively. Fig. 10 shows the outlet water temperature at the different values of mass flow rates. The average values of the outlet temperature of water were found to be (120.84, 63.82 and 46.08 ^oC), while the maximum values, at midday, were (160.5, 76.4 and 50.4 ^oC), respectively. It is shown that the outlet water temperature rises gradually until time of about 12 pm and then begins to drop due to increasing the solar radiation falling on the solar collector and to the shadow effect of the grooves of the absorber surface which reduces the energy collected and increases thermal losses of the solar collector. It can be say, during the morning, all radiation was readily absorbed by the receiver tube, and so, the mean tube temperature and outlet water temperature increase at minimum heat loss. Fig. 11 shows the useful heat gain of water for the three cases of mass flow rates with average values of (798, 732 and 732.5 W), and maximum values, at midday, of (1150.6, 1031.6 and 785.4 W), respectively. Fig. 12 shows the instantaneous thermal efficiency of the solar collector during daylight hours. There is a gradual increase in efficiency due to cold water at the beginning of the day and to a gradual increase in the heat gain until midday and after that it starts to decrease gradually. Also, it is noticed that the system has average values of the thermal efficiency of (50.3, 49.51 and 44.31%) for the corresponding mass flow rates, and maximum values, at midday, of (68.6, 67.4 and 47.8%), respectively. It is showed from the figure that the thermal efficiency of the collector is inversely proportional to the mass flow rate approximately during the mid period of daytime. It could be concluded from the results, that decreasing the water mass flow rate, causes increase in the temperature of the water outlet from the collector and thus, increasing the useful heat gain and the thermal efficiency too, because decreasing the water flow rate will slow the water flow and thus causes prolonging the heating time of the water during the flow in the helical tube. Consequently, higher temperatures are obtained, and vice versa.

6. Conclusions

The thermal performance of a parabolic trough solar concentrator could be enhanced by using a modified solar receiver represented in the form of a helical coiled tube, placed on the focal line of the parabola, and directed with two-axis solar tracking system. The experimental performance investigations confirm that the helical tube designed for the parabolic trough concentrator with tracking system is more efficient. From the experimentation and thermal performance evaluation, it is found that the incident solar radiation and tracking action are very important parameters which directly affect the thermal performance of the parabolic solar trough concentrator. The proposed solar concentrator with helical tube generates hot water could reach to steam phase up to 160^{o}C. Thus, this system prototype could be utilized for heating water as well as steam generation for domestic and low scale applications. In this concentrator prototype, the maximum and average values of the thermal efficiency is found to be of 68.6% and 50.3%, respectively, at water mass flow rate of 8 L/h.

Table 1 Specifications of the PTSC system

Parabolic reflector		Helical coiled tube receiver		Glass tube		Tacking system		Charging system	
material	stainless steel	material	99.9% Copper	material	Borosilicate glass	tracking mechanism	electro-optical (LDR)	Solar PV panel	
aperture area	1.755 m^2	thermal conductivity	401 W/mK	length, L_g	1830 mm	tracking modes	2-axes	model	LJ-C12/308
aperture width	1 m	absorption coeff. of coated paint	~ 0.9	diameter, D_g	58 mm	DC Motor-1		material	Mono-crystalline Silicon
length-to-aperture ratio	1.755	coil diameter, D_C	41 mm	thickness, t_g	1 mm	type	DC gear box	P_{max}	13W
thickness	1 mm	helix length, L_C	1835 mm	weight	1.2 Kg	motion	axial	V_{mp}	12V
rim angle	90°	coil pitch, p_C	11.42 mm	thermal expansion	3.3×10^{-6} °C	voltage & current ratings	12V, 0.4A	I_{mp}	1.09A
concentration ratio	17	no. of coil turns, N_C	116	absorptance	> 92%	DC Motor-2		V_{OC}	13.8V
height	0.25 m	pipe dimension, L_p* D_p* t_p	15240*6.35*0.61 mm	stagnation temperature	> 200°C	type	linear	I_{SC}	1.17A
focal length	0.25 m	working fluid	water	emittance	< 8%@80°C	motion	tilting	max. system voltage	600V
reflectivity	0.93	mass per coil	1.494 kg	transmissivity	> 0.95	voltage & current rating	12V, 1.2A	size	520*230*22mm
		hardness	> 40-50 VPN	heat loss	< 0.7W/m²°C	Control circuit		Charge controller	
		tensile strength	205 MPa/min			controller	ATmega16L Arduino UNO	model	LP12/24-10A
		yield stress	8 MPa			relay board	4-channel 5V, Model 10A	voltage & current rating	12/24V DC 10A
								max.charging voltage	14.4 / 28.8V
								charging battery	12V, 14Ah

Table 2. Calculating the required operating values for the motors

Motor type	Current (A)	Voltage (V)	Power (W)	Operation time (h)	Consumed Energy (W.h)
X-axis motor (axial motion)	0.4	12	4.8	0.0319	0.1531
Y-axis motor (tilting motion)	1.2	12	14.4	0.0319	0.4594
Water pump	0.83	12	9.96	14.333	142.76
Σ				14.397	143.373

Table 3. Specifications of measuring instruments

Items	Type	Resolution	Accuracy	Range
Temperature recorder	BTM-4208SD Type K thermometer-12 channel	1 deg. / 0.1 deg.	± (0.4%+1°C)	- 100 to 1300°C
Solar power meter	TES-1333R Data logging	0.1W/m²	±10W/m²	2000 W/m²
Wind speed meter	Kaindl Windmaster 2 Wind Gauge	0.1m/s	±4 %, ±1	0.7 – 42 m/s
Flow meter	LZM-6T ZYIA Rotameter	---	±4	100-500 mL/min

Fig. 1. Experimental setup

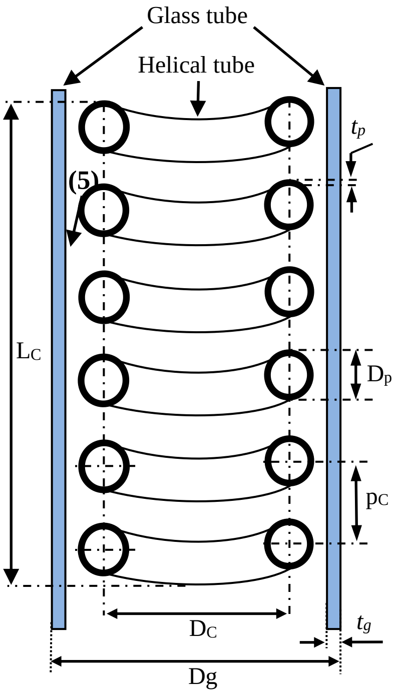

Fig. 2. Schematic cut-away view of a helical coil tube inserted in a glass tube.

(a)

(b)

Fig. 3. (a) DC gear box motor for axial motion, (b) Linear DC motor for tilting motion.

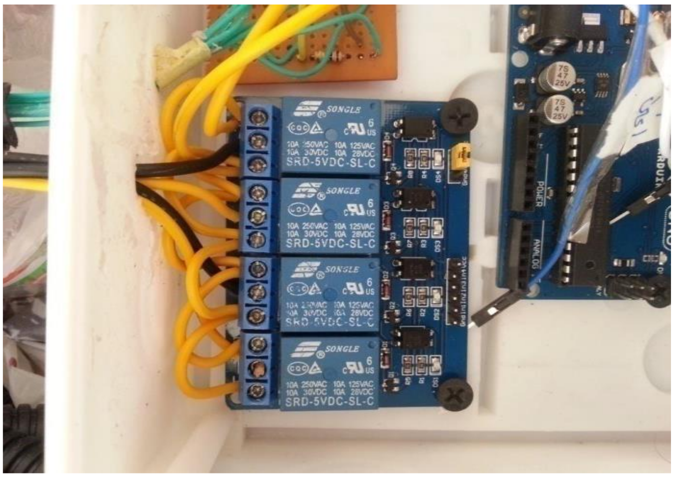

Fig. 4. Control circuit: connecting the relay circuit with the Arduino and motors.

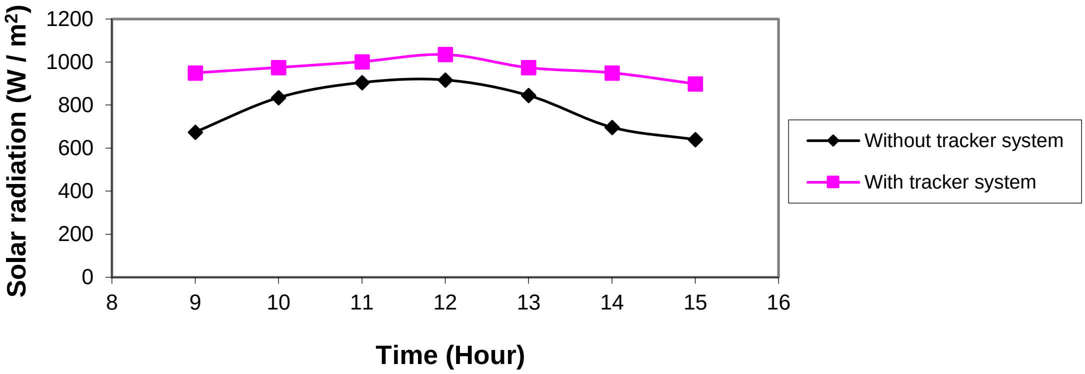

Fig. 5. Solar radiation intensity during daytime on (16th and 17th) April 2020

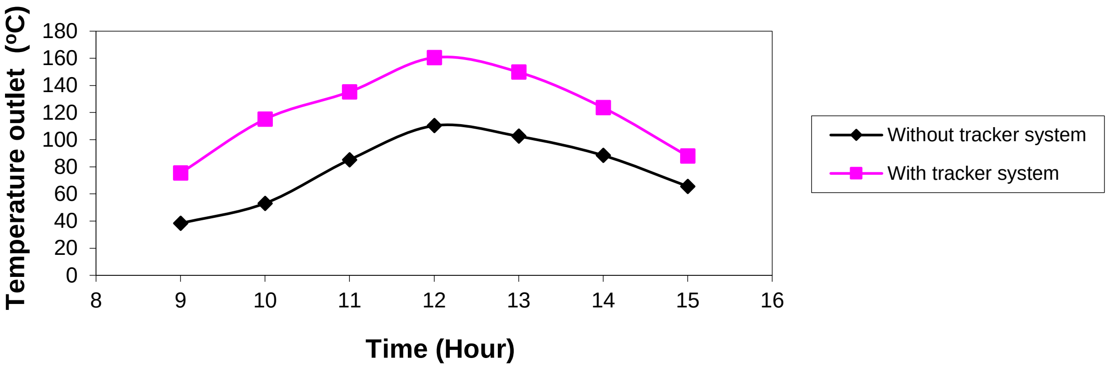

Fig. 6. Outlet water temperature during daytime on (16th and 17th) April 2020

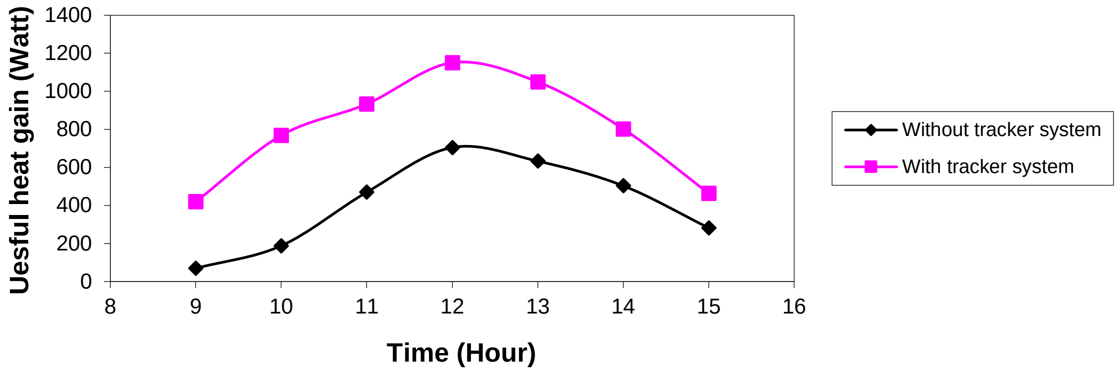

Fig. 7. Useful heat gain during daytime on (16th and 17th) April 2020

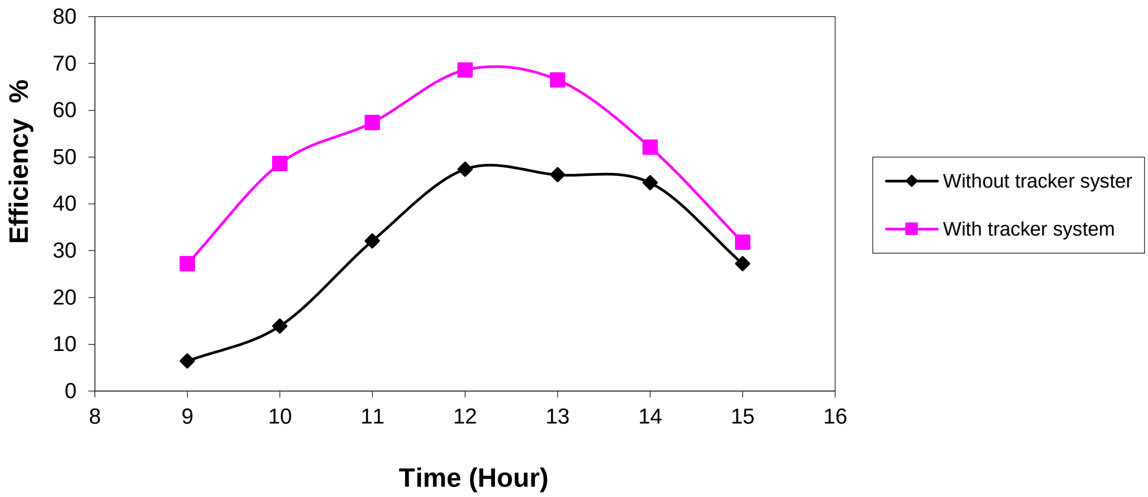

Fig. 8. Thermal efficiency during daytime on (16th and 17th) April 2020

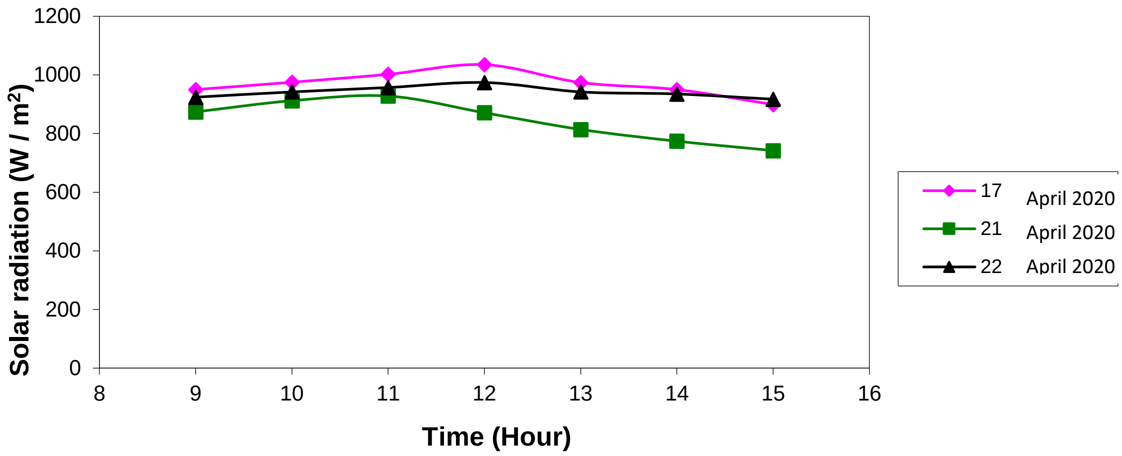

Fig. 9. Solar radiation intensity during daytime with tracking system at different flow rates

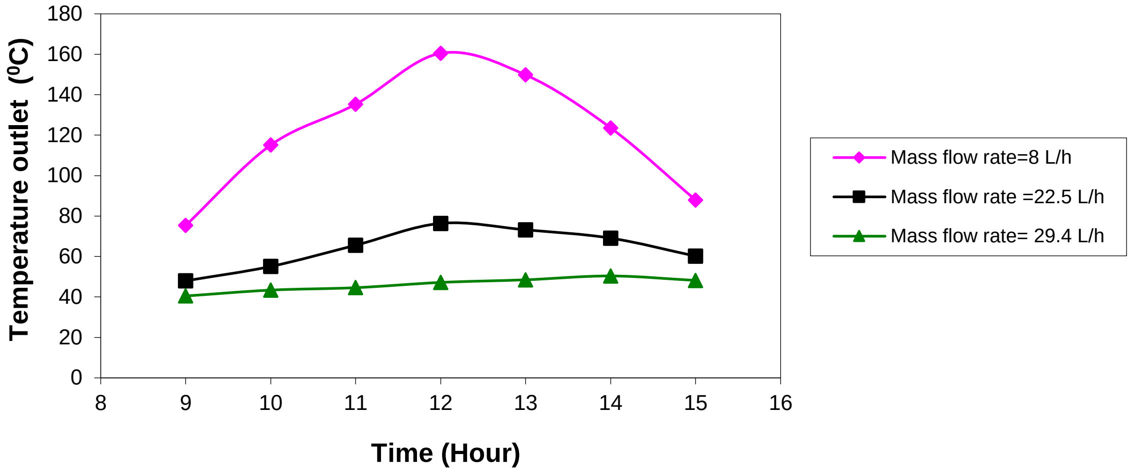

Fig. 10. Water outlet temperature during daytime with tracking system at different flow rates

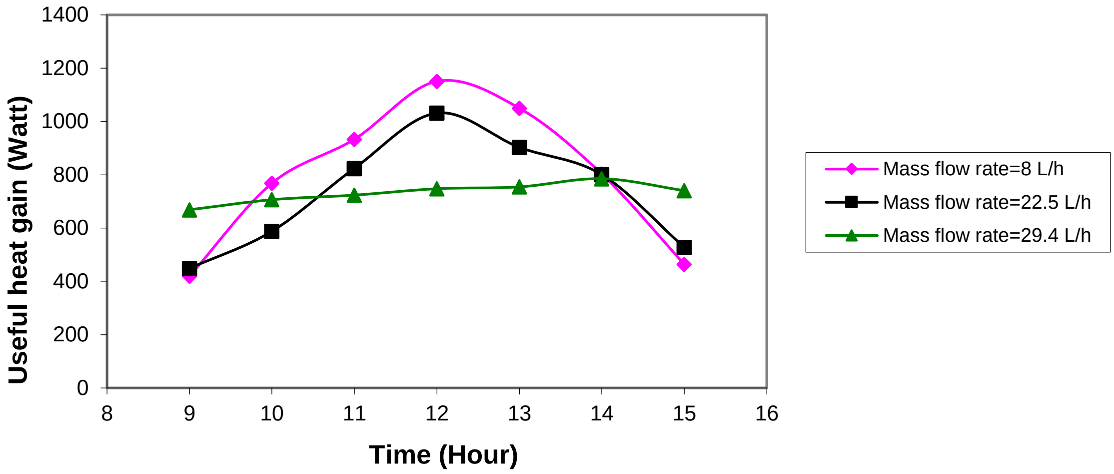

Fig. 11. Water useful heat gain during daytime with tracking system at different flow rates

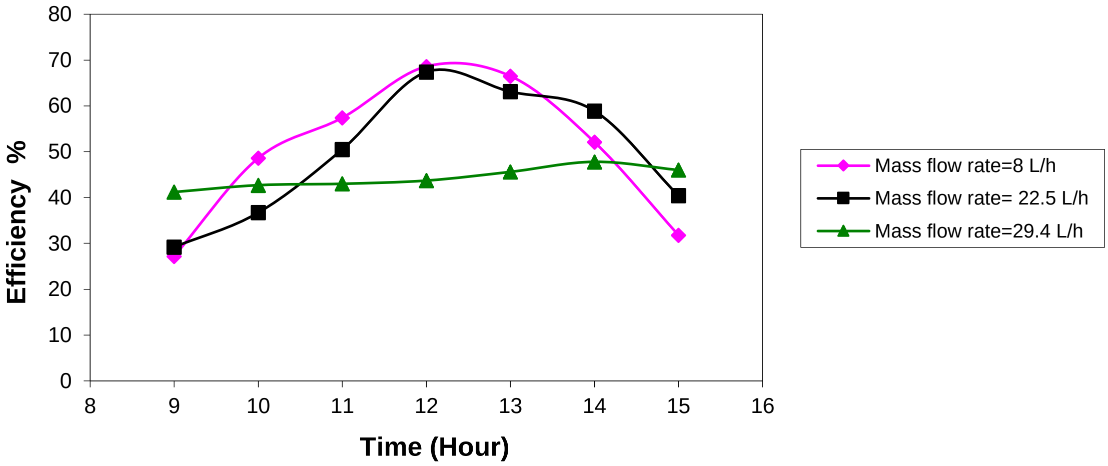

Fig. 12. Thermal efficiency during daytime with tracking system at different flow rates

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