Design and implementation of an automatic control for two axis tracking system for applications of concentrated solar thermal power

Eng. Laith Mohsen Reda
Mohsen.laith12@yahoo.com
Engineering construction office / Maintenance Department

Abstract

The present work represents a design and implementation of an automated two-axis solar tracking system using local materials with minimum cost, light weight and reliable structure. The tracking system consists of two parts, mechanical units (fixed and moving parts) and control units (four LDR sensors and Arduino UNO microcontroller to control two DC servomotors). The tracking system is fitted and assembled together with a parabolic trough solar concentrator (PTSC) system to move it according to information come from the sensors so as to keep the PTSC always perpendicular to sun rays. The experimental tests have been done on the PTSC system to investigate its thermal performance in two cases, with tracking system (case 1) and without tracking system (case 2). The experimental results show that the average solar radiation falling on the PTSC prototype in the two cases during the same time is (854, 701 watt/m^2), respectively, which means an increase in the solar radiation about 21.8 % when using tracking system. It is found that the average useful heat gain output of solar collector is (376.2, 252.6 watt) in the two cases, respectively, so it increases about 48.9 % when using the tracking system. Also, the average thermal efficiency of the PTSC is found (20.7, 26.5 %) in the two cases, respectively, which means an increase in the average efficiency by 28% with tracking system compared with the fixed case.

Keywords*: tracking system, Arduino, solar collector*

1. Introduction

Solar tracking system is very important technology, utilized in the advancement of solar energy applications, especially in the high power solar concentrator which directly transfer the solar energy into electrical or thermal energy. Solar tracking precision with high degree is requested to guarantee that the solar collector is capable of utilization the peak solar energy during the daytime. Solar concentrator with high power, like parabolic trough, central receiver system, parabolic dish, etc are commonly used in the collecting solar energy applications. The solar trackers follow the track of sun in the horizontal and vertical plane. For the sake of this capabilities, the two axis trackers output higher power than the single axis trackers. Roth, et al. [1] designed a two axis solar tracker. This tracker enables to get automated measure for forthright solar radiation with a pyrheliometer. The tracker, in the active mode of operation, utilizes the signal come from a sun detecting linear sensor for controlling the pointing. To direct the instrument platform, two stepper motors were used, making the sunrays falling on the center of the sensor. Mamlook, et al. [2] designed and implemented a two axis solar tracker. A programmable logic controller PLC was used to direct the two axis sun tracking surface. The results were compared with the fixed system case at a surface tilted 32^o to the south. Initially test measurements pointed out that using the two axis solar tracker would daily elevate the thermal energy collection more than 40%. Sungur [3] proposed a dual axis tracking system using formulas to calculate the solar azimuth and altitude angles yearly for an interval of one year. Khan, et al. [4] had designed and built a sun tracking system controlled by microcontroller. The tracker senses the sunlight intensity via Light Dependent Resistors (LDRs) to be utilized for driving stepper motors to direct the Photovoltaic (PV) panels according to the sun position. Pineda and Arredondo [5] designed and carried out a two axis sun tracking system. The tracker senses the peak brightness light point in the sky by building a sensor based on a geodesic dome. Yousif [6] presented a mechatronic tracking system to follow the sun position depending on four sensors mounted on the solar panel frame. A microcontroller ATmega16L was used to control the system. It was found in this study that the output power gain for the two axes solar tracking panel was 31.5% more than the fixed solar panel. Sadyrbayev, et al. [7] designed a two axis sun tracking system, with four photo resistors, controlled by LM324N microcontroller. The results showed that the solar tracker system generated a 31.3% higher power.

Parabolic trough solar concentrator PTSC system for water heating is one of various technologies that excellently confirm solar energy. It, commercially, has been used to generate high pressure steam in the power generation units. Also, it could be used in residential and commercial applications with small scale [8]. A small scale generation system could be utilized to generate a process heat with intermediate temperatures reaches 150°C. This temperature is enough for most processes of small factories, like paper production, food canning, sterilization, air-conditioning, refrigeration, etc. The thermal performance of this kind of sun concentrator could be enhanced highly via using one of the sun tracking topologies to concentrate the sunrays on the focal point. Basically, the tracking action depends on the axis of the sun beam reflector. A comparative investigation for various modes of tracking had been studied comprehensively in the literature [9,10]. These studies demonstrated that adopting the two axis tracking mechanism will lead to highly increase in the output of the system energy and enhances the contribution in solar energy. It had been described in the literature that the two axis sun tracker dissipates more energy than the single sun tracker because of the additional power control requirement. So, utilizing the two axis technique cannot be considered except if the quantity of produced energy is compensating to the extra elements and cost of maintenance.

The aim of this work is to design and implementation of a microcontroller based two-axis sun tracker to direct the PTSC prototype consciously toward the sun to enhance its thermal performance. An experimental study is carried out on the prototype to evaluate the system thermal performance under the local climate.

2. Modes of Tracking

Generally, there are two modes of tracking for the PTSC; single axis tracking and two axis tracking. The two axis tracking follows both of the sun's changing azimuth and sun's changing altitude to focus the parallel sunrays falling on the reflectors perpendicularly on the receiver tube, while the single axis tracking collector is directed to a north-south and follows the sunrays from east to west as shown in Fig. 1 (a, b and c).

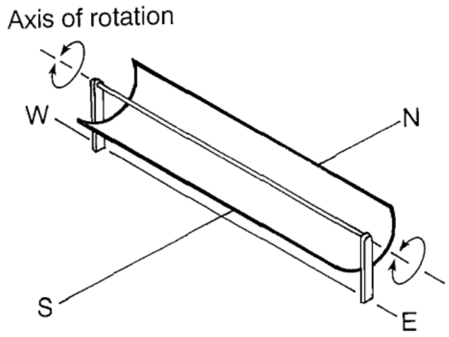


Fig .1a. One axis tracker

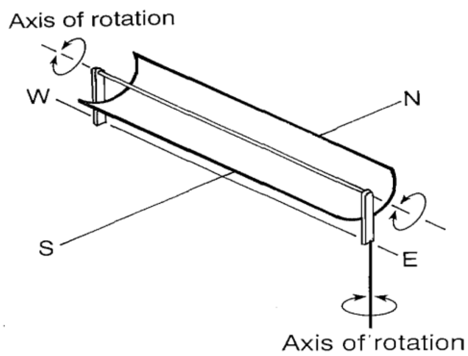


Fig.1b. Two axis tracker

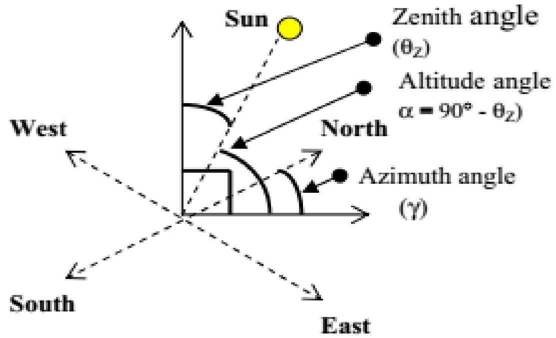


Fig.1c. (Azimuth and solar altitude angles)
Fig. 1. Modes tracking system [11]

A tracking mechanism must be reliable and able to follow the sun with a certain degree of accuracy, come back the thermal collector at the end of daytime to its initial location, and also track the daylight when it is cloudy. Fixed collectors producing heat or electricity all year round are usually fixed and tilted at an angle equal to the installation site latitude which directly opposing the sun. Therefore, the thermal energy accumulated by the solar collector during both summer and winter is less because of the sun's changing altitude. The use of the tracking mechanism elevates the amount of solar energy received by the solar collectors resulting higher output power.

Initially, the PTSC is a flat plate with linear tube collector placed on the mechanical structure of the tracking system. A solar photovoltaic PV panel might be mounted on the PTSC frame in order to capture the entire light incident on it and converts it into electrical energy required for the tracking action. To stabilizes the solar PV panel electric output and minimizes any fluctuations in the 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. An Arduino "microcontroller based board" is used to control all the system processes to be implemented as expected. The Arduino takes analogue input from light dependent resistances sensors LDRs and supplies the servomotors with electric power. According to the location of the sun, the Arduino controller analyses the signals come from the LDRs. The LDRs' resistance and thus the value of current flowing into the Arduino is varying, depending upon which of the two facing LDRs has higher falling light on it. The voltage variation is then converted into input signals driving the motors. Two motors are mounted on the PTSC axes, responsible for the dual-axis movement of the tracking system. This causes the PTSC system to tilt in the direction of the LDR causing decrease in its resistance to the lowest value and hence, guarantees fall the maximum sunrays on the PTSC. This noticeably, raises the amount of light energy captured and then transferred into heat energy.

3. Hardware Implementation of Tracking System

The tracking system is mainly consisting of two parts, mechanical unit and electrical control unit.

3.1 Mechanical unit

The mechanical unit of the tracking system consists of fixed part and moving part. The fixed part, called the base, is very important to fix the whole concentrator system on it. The moving part is responsible to provide two types of motions of axial and tilting. The axial motion is employed to move the collector from east to west. This movement is the most effective in the solar tracking system. The movement in this direction is done via using a 12V, 0.1A DC gear box as shown in Fig. 2a. The tilting motion is utilized to drive the collector to upper and lower. This movement can be directed by using a 24V, 0.42A DC motor to produce a linear movement. This motor is installed on the moving part of the PTSC system using welding and rotates through bolts as shown in Fig. 2b.

Fig. 2a. DC gear box (axial motion)

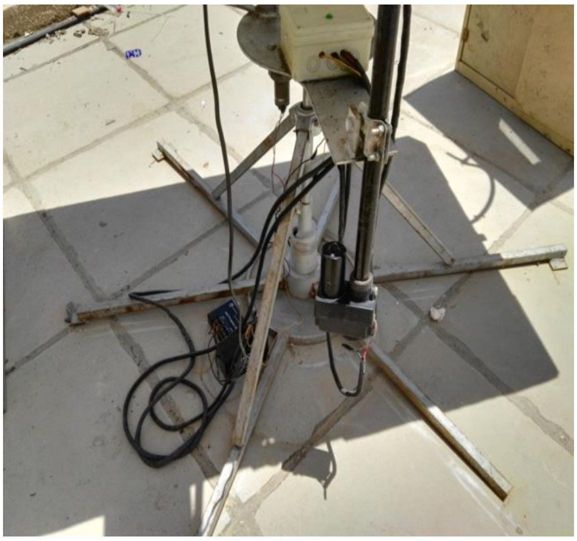
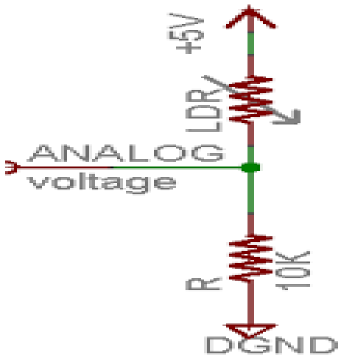


Fig.2b. DC motor movement (tilting motion)

3.2 Control unit

The control circuit consists of, Arduino UNO, four light dependent resistances (LDRs) and four channel relay circuit. The Arduino UNO is a board electronic development; comprise of an electronic circuit open source with a microcontroller based single board. It is programmed by a computer and designed to make the process of utilizing interactive electronics in multidisciplinary projects more easily. Four LDRs were used in order to sense the solar radiation and track the movement of the sun and in order to make solar radiation perpendicular to the collector. The LDR resistance depends on the intensity of the radiation falling on them, the more the intensity of the radiation incident, the less resistance, and the lower the intensity of the radiation falling on this resistance, the greater the resistance. This is to take advantage of this feature when changing the value of resistance while changing the intensity of the radiation falling on them. The current flowing through them will change and thereby change the voltage on the resistance according to Ohm's law. Fig. 3 shows the connection of the LDRs to the Arduino UNO and 10KΩ resistance for the purpose of voltage divider necessary for the process of the solar tracking.



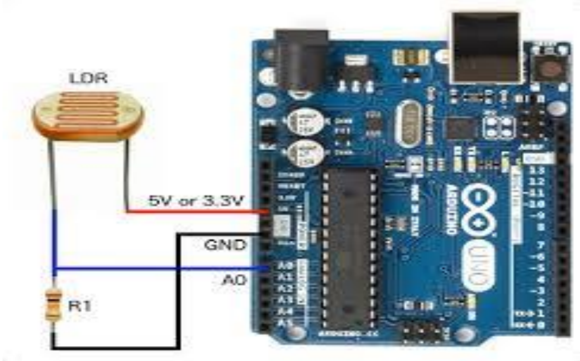


Fig.3. LDR connecting with Arduino UNO [12]

Four channel relay circuit board is used to run the DC motors, used for directing the solar tracking process, via connecting this circuit between the Arduino and the motors. The circuit is fed from a 6V DC source. The relay circuit receives the electrical signals coming from the Arduino; its work is depending on the software loaded on 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 PV panel, 12V 12Ah Sealed Lead Acid battery, and 12V charge controller should be used. The block diagram in Fig. 4 shows operation steps the two axis tracking system. The tracking process can be demonstrated as in the flowchart shown in Fig. 5.

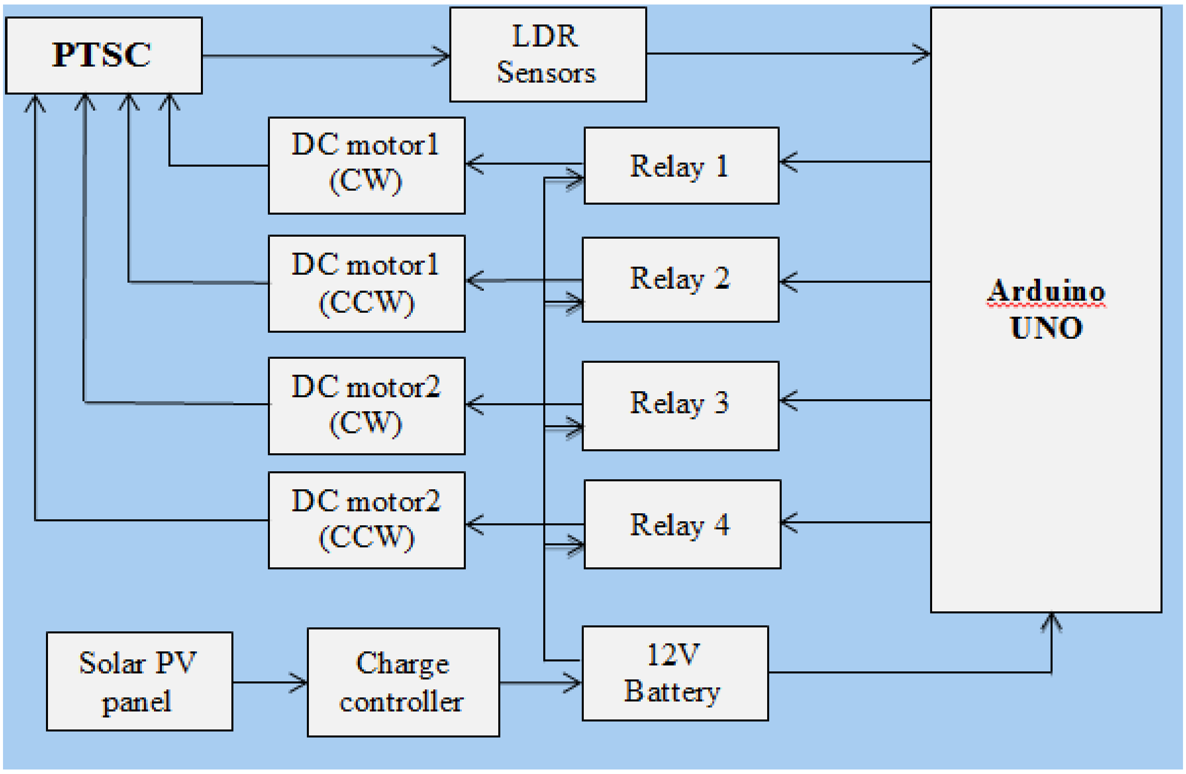


Fig.4 Block diagram of the two axis tracking system

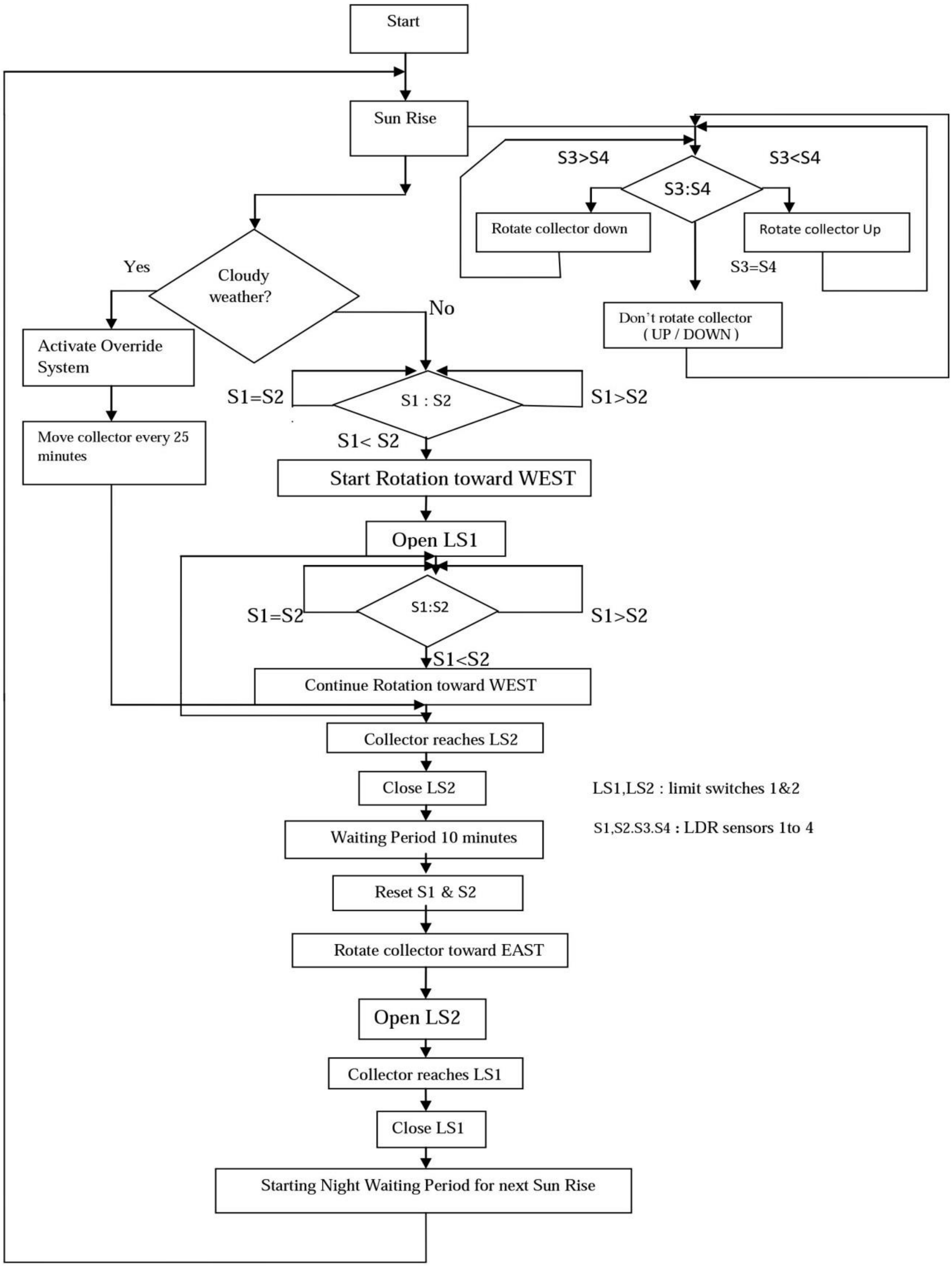


Fig.5. Flow chart of the two axis tracking process

4. Design of the Solar PV Panel

The PV panel used as a self DC power supply to fed the two DC motors as well as a water pump without the need to external AC power supply. The PV panel power can be designed depending on the electrical specifications of the motors and water pump used and the time duration of the PV panel through the daytime. The design of the PV panel power was carried out on Date 24/3/2016. The operation time was from the sunrise time at 7:03am to Sunset time at 5:26pm. The system uses two DC motor to move the PTSC system in the X-axis and Y-axis directions, and the 12V DC water pump to recycle the water in the system. The axes motors were permitted to move two seconds every quarter of an hour, through the whole running time. While the water pump was running continuously. Table (1) shows current, voltages, power, running time and energy for each motor used in the system. This table represents the rated values of all motors as well as the calculations necessary for designing the PV panel and thus specify the required DC battery and the charge controller.

Table (1) Operation values for the DC motors

Device	Current (A)	Voltage (V)	Power (W)	Operation time (hour)	Consumed Energy (W.h)
X-axis motor axial motion	0.1	12	1.2	0.02307	0.027
Y-axis motor tilting motion	0.42	24	10.08	0.02307	0.232
Water pump	1	12	12	10.383	124.6
Σ				10.42914	124.859

The total PV cell power for this design = $\frac{124.859\text{W.h}}{10.42914\text{Hour}} = 11.972$ W.

The value of the energy required that is enough to supply the tracking system with electricity is:
$\frac{124.859\text{W.h}}{12\text{V}} = 10.4$ A.h.

As a result, a 12V, 13W PV panel is enough to be used for charging a 12V, 12Ah 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 the battery.

5. Description of the Parabolic Trough Solar Collector

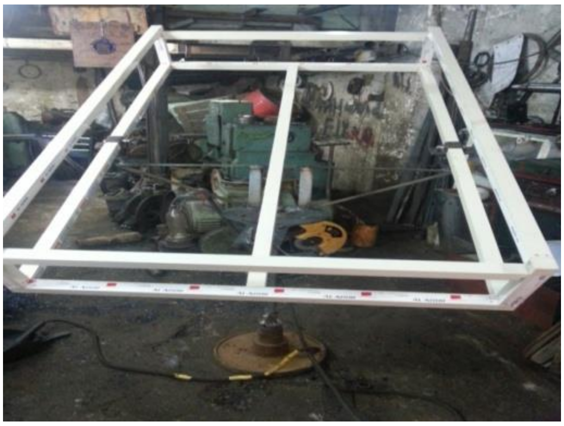
The PTSC system has major components; reflector, receiver, support structure, working fluid circulation system and tracking system. The reflector was coated with polished aluminium sheet (0.5 mm thickness) having reflectivity of 0.87. A receiver tube of copper material was coated with black zinc having absorptivity of 0.94. Thin layer of coating was used so as to minimize the resistance of heat flow through the coat to the pipe and to the working fluid. Support structure was built using steel to provide strong mechanical support against high wind speed and harsh environmental conditions. Table (2) contains all the dimensional specifications of the PTSC and other parameters.

Table (2) PTSC system specifications

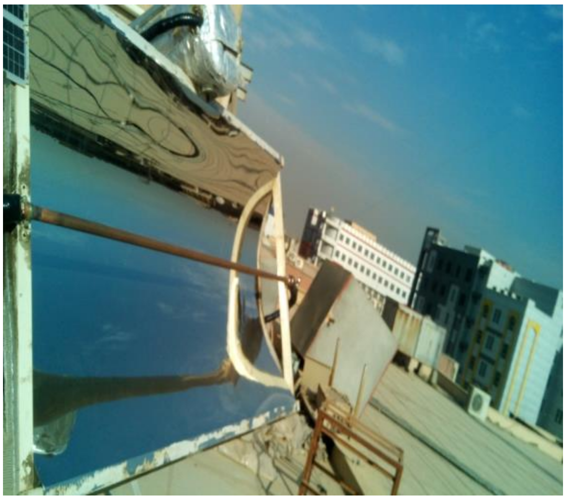
Item	Value / Type
Collector aperture area	1.612 m^2
Aperture width	1m
Length-to-Aperture ratio	1.755
Rim angle	90°
Receiver diameter	0.025 m
Tracking mechanism type	Electro-optical
Mode of tracking	Two axes tracking
Concentration ratio	10.5
Focal length	0.250 m

6. Experimental setup and Instrumentation

The experimental setup is shown in Fig. 6.



(a)



(b)

Fig. 6. Experimental setup (a) frame, (b) PTSC

The experimental setup consists of the PTSC directed by a tracking system and combined with a storage water tank. A tank of 40 litres capacity kept at 0.5 m above the PTSC level to maintain natural flow of working fluid (water) inside the PTSC with close loop and without loading water. In this experiment, the water temperature at inlet, outlet and ambient was measured using Thermometers (Model: BTM-4208SD**)**, sensor type K thermocouple. The water mass flow rate of (20 L/h) has been measured using flow meter. The water has specific heat of 4.2 Kj/Kg.^{o}C. A solar meter (Model: TES-1333R data logging solar power meter) used to measure the intensity of solar radiation during time interval (9am-3pm) according to tilt angle for the PTSC. The PTSC system was directed by the tracking system controlled by an Arduino UNO controller board. The solar energy radiation sensors are mounted on the PTSC frame and send electric signals to the control circuit. The control circuit converts these signals to specified motors via a drive circuit to direct the PTSC toward the sunlight. These motors, in turn, direct the location of the PTSC when peak sun radiation intensity is received at the aperture. These motors were supplied with the required power from a 12V, 12Ah DC battery, charged via a 12V, 13W solar PV panel. The PV panel was designed according to the electrical energy required to feed two DC motors and a DC circulating water pump. The DC motion motors are programmed to move for 2sec after each stop of 15 min during the daily work period, while the water pump works continuously to circulate water through the collector. The measurements of (solar radiation, inlet water temperature to receiver tube, outlet water temperature from receiver tube) were carried out every hour through time daily from (9am-3pm). The useful heat gain (the amount of heating absorbed by working fluid) and the thermal efficiency of the PTSC were determined according to the measurements parameters and they can be obtained from Equations (1)-(4):

$$Q_U = m^* C_P (T_{oulet} - T_{inlt}) \quad \text{... (1)}$$

$$(Q_U)_{ave} = \frac{\sum Q_U}{N} \quad \text{... (2)}$$

$$\eta = \frac{m^* C_p (T_{outlet} - T_{inlet})}{I A_c} \quad \text{... (3)}$$

$$(\eta)_{ave} = \frac{\sum \eta}{N} \quad \text{... (4)}$$

7. Results and Discussion

Fig. 7 shows the variation of the average solar radiation intensity measured in the 26 of April 2016 using solar meter at the fixed case (without using tracking system) of the PTSC and in the 27 of April 2016, the average intensity solar radiation on the same PTSC was measured using two-axis tracking system. The figure shows that the solar radiation increases as day passes from morning to noon and gradually reduces after 12:30pm. In the case of non tracking system, the solar radiation available was in the range of (580 - 890 W/m^2). While it was found that the solar radiation available was in the range of (735 - 922 W/m^2), when using two-axis tracking system. It could be concluded from this figure that the average obtained solar radiation for the fixed collector during interval time daily (9am-3pm) was (701 W/m^2), while with tracking system, the average solar radiation become (854 W/m^2). This means an increase in solar radiation about (21.8 %) when using tracking system compared with the fixed case. Fig. 8 shows the effect of solar radiation on receiver outlet temperature of water in the 26 of April 2016 at the fixed case of the PTSC and in the 27 of April 2016 at the tracking case. From the figure, it can be shown that the outlet temperature of the water is gradually raised from morning to noon and gradually reduced after 12:30pm when the outlet temperature is in the range (28.4-74.3ºC). The average value of outlet temperature is 59.5ºC through time daily from (9am-3pm) for non-tracking system. In the case of tracking system case, the outlet temperature of water was in the range (36.3-89.5ºC) and the average value of outlet temperature through time daily reaches up (73.3 ºC). From the figure, it can be concluded that there is an increase in the outlet temperature of the water about (23%). Also, it is noted from the figure, that the outlet water temperature rises gradually until 12:30 then begins to drop because of the solar radiation falling on the solar collector decreases and shadow effect of the grooves of the absorber surface which reduces the energy collected and increases thermal losses from the solar collector. Also, it was observed that during morning, all radiation was readily absorbed by receiver tube, so mean tube temperature and outlet water temperature increase at minimum heat loss. Fig. 9 shows the useful heat gain in the 26 of April 2016 at the fixed case of the PTSC and in the 27 of April 2016 at the tracking case. It can note that the useful heat gain of the solar collector for non-tracking system has an average value reaches up to 252.6 watt through time daily from (9am-3pm), while it reaches to 376.2 watt for tracking system case, through the same time interval. This means an increase of about 48.9% when using tracking system for solar collector compared with the fixed case. Fig. 10 shows the instantaneous efficiency of the solar collector during daylight hours in the two cases of tracking. It is noted a gradual increase in efficiency due to cold water at the beginning of the day, this due to a gradual increase of the heat gain until the time 12:30 and after that it starts decrease gradually. From this figure, it is noted that the average efficiency of the solar collector during time daily between (9am-3pm) for non-tracking system reaches up to (20.7%), while, with using tracking system, the average value of efficiency reaches (26.5%). This means the increase of about (28%) when using tracking system for solar collector as compared with fixed system case.

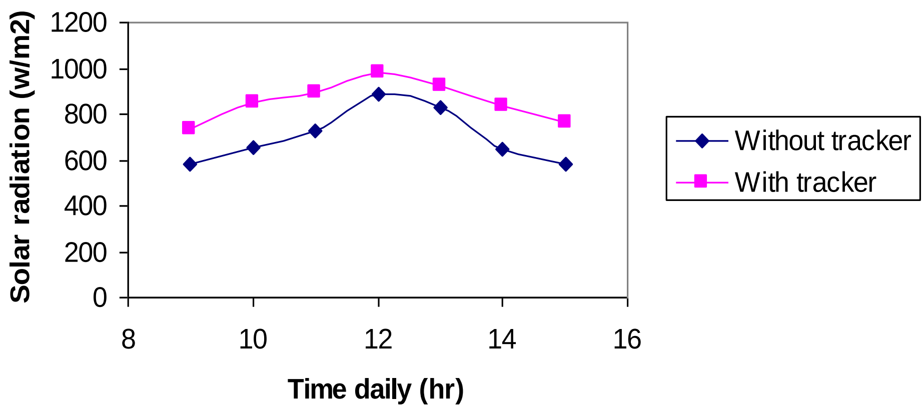


Fig. 7. Solar radiation with time on the (26th and 27th) April 2016

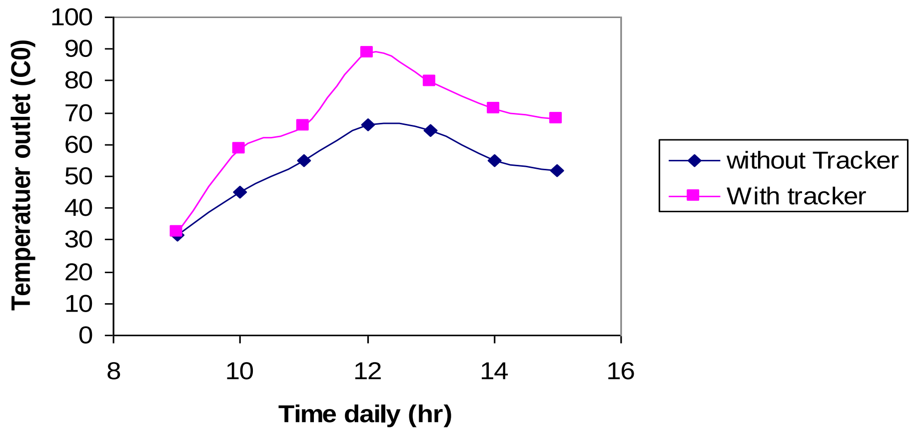


Fig. 8. Outlet temperature with time on the (26th and 27th) April 2016

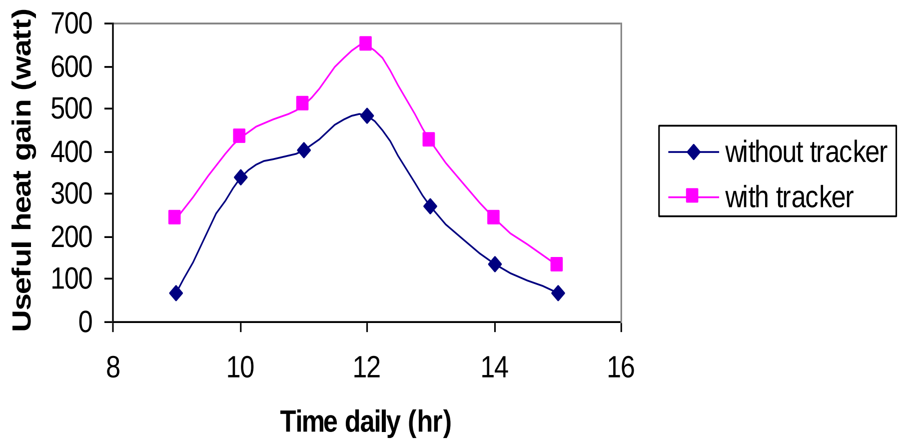


Fig. 9. Useful heat gain with time on the (26th and 27th) April 2016

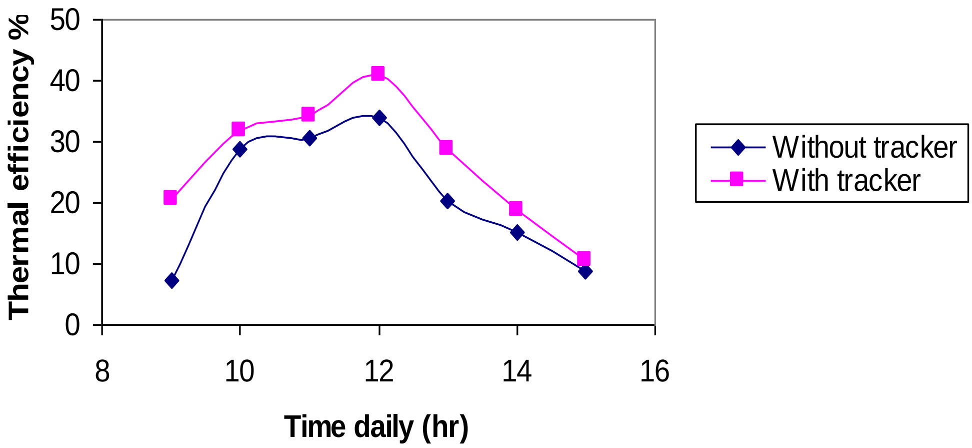


Fig. 10. Thermal efficiency with time on the (26th and 27th) April 2016

8. Conclusions

This paper focuses on the design and implementation of an automatic control for two axis tracking system for the applications of the concentrated solar thermal power. A parabolic trough solar concentrator is proposed to be used for generation a hot water suited for domestic and industrial process heat applications. From experimentation and thermal performance evaluation, the following conclusions are drawn: The incident solar radiation and the mode of tracking system are very important parameters which directly affect the performance of the PTSC. Using the tracking system to direct the PTSC to the sunrays enhanced the solar concentrator performance. The concentrator has been generate a hot water up to 89 C^0 and raised the average instantaneous efficiency of the PTSC to 23% when using two-axis tracking comparing with the fixed system.

Nomenclature

Abbreviation	Meaning of Abbreviation
Ac	Aperture area (m^2)
Cp	Specific heat capacity of water
	at constant pressure (kJ/kg.K)
I	Solar radiation (Watt/m^2)
m^*	Mass flow rate (Kg/s)
N	Number of reading measurement
Q_u	Useful heat gain (Watt)
Q_{ave}	Average useful heat gain (Watt)
Tinlet	Fluid inlet temperature (°C)
Toutlet	Fluid outlet temperature (°C)
η	Thermal efficiency (%)
η_{ave}	Average thermal efficiency (%)

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تَصميم وتَنفيذ تَحكّم آلي لمنظومة تَتبع ذاتُ محورين لتطبيقات الطاقة الحرارية الشمسية المُرَّكزة

مهندس. ليث محسن رضا

*البريد الألكتروني:*mohsen.laith12@yahoo.com

دائرة الأعمار الهندسي / قسم الصيانة

الخلاصة

يُمثل العمل الحالي تصميم وتنفيذ منظومة تتبع شمسي ذاتية الحركة ذات محوريين بأستخدام مواد محلية بأقل كلفة وأخف وزن وموثوقية بناء. منظومة التتبع تتألف من جزأين: الوحدات الميكانيكية (الأجزاء الثابتة والمتحركة) ووحدات التحكم الكهربائية (من اربعة متحسسات ظوئية من نوع LDR ومسيطر دقيق نوع أردوينو الذي يقوم بالسيطرة على محركيين نوع ذاتي الحركة يعملان بالتيار المستمر) . إنّ منظومة التتبع ثنائية المحاور تأتي مثُلائمة ومُجمتعة سوية مع المُركّز الشمسي ذو القطع المكافيء لتحريك المُركز وحسب المعطيات القادمة من المتحسسات الضوئية لكي تُبقى المُركز الشمسى بشكل دائم عمودياً على الاشعة الساقطة من الشمس .أجريت الأختبارات التجربية على المُركز الشمسي لتقييم الأداء الحراري في حالتين: (الحالة الأولى) بأستخدام منظومة التتبع الشمسي و(الحالة الثانية) عند عدم استخدامها. بَيّنت النتائج التجريبية المستحصلة بأن مُعدل أشعة الشمس الساقطة على المُركز الشمسي في الحالتين هي على التوالي (٨٥٤ واط/متر^{٢} و ٧٠١ واط/متر^{٢}) وهذا يعني زيادة في معدل الأشعاع الشمسي حوالى ٢١,٨ % عند استخدام منظومة التتبع. لقد وُجدَ بأن معدل الحرارة المفيدة المكتسبة للمُركز الشمسي لنفس الفترة الزمنية وللحالتين أعلاه هي على التوالي (٣٧٦,٢ واط و ٢٥٢,٦ واط) وهذا يعني زيادة حوالى ٤٨,٩ % عند استخدام منظومة التتبع وكما وجد بأن مُعدل الكفاءة الحرارية للمُركز الشمسي في حالتي التتبع كانت على التوالي (٢٦,٥% و ٢٠,٧%) وهذا يعني زيادة بمقدار ٢٨ % عند استخدام منظومة التتبع ثنائي المحاور بالمقارنة مع المنظومة الثابتة.
