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EXPERIMENTAL PERFORMANCE EVALUATION OF PARABOLIC TROUGH SOLAR COLLECTOR FOR STEAM GENERATION

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ABSTRACT

This paper presents the experimental performance evaluation of a parabolic trough solar collector (PTSC) for hot water and low enthalpy steam generation. A prototype of a PTSC with a 90° rim angle and a concentration ratio of 20 was constructed using mild steel as a support of the reflective mirror strips pasted on the bent sheet that formed the trough. The receiver is a copper pipe of circular cross-section, contained within glass envelope made from borosilicate material. The investigation was carried out at Department of Mechanical Engineering, Bayero University, Kano-Nigeria climatic conditions (12.05°N, 8.53°E) during selected days of the months of October, November, February, March, April, and May. The tests were conducted using a suitable solar collector test standard and the efficiency curve for the PTSC was estimated. In the performance analysis of the PTSC, the effects of collector inlet temperature, solar intensity and useful energy gain on the mass flow rate of water as a working fluid were investigated. The results show that the equation for thermal efficiency is comparable to similar collectors available in the literature; the intercept is 0.532 and the slope -0.1097. The highest and lowest temperatures of 133.5°C and 56.2°C were obtained in the month of April and October respectively. These temperatures obtained established the technical feasibility of using PTSC in Kano-Nigeria, for industrial process heat applications requiring thermal energy at temperatures up to 133.5 ºC.

Keywords: performance, useful heat gain, thermal efficiency,

INTRODUCTION

The parabolic trough solar collector (PTSC) is among the CSP systems available, the PTSC technology is one of the matured and appropriate technology in the solar energy exploitation, the proven and of the low cost large-scale solar power technologies available (Mao *et al.* 2014).

Nigeria as the 32nd largest country in the world with an area of 923, 768 km^2, lies between latitudes 4º, 14ºN and longitudes 2º and 15ºE. It falls within a high sunshine belt, the total average of global solar irradiance on the horizontal surface ranges between 1461 - 2337 kWh/m^2. These values correspond to the average daily range between 4 and 6.4 kWh/m^2.day. Nigeria's map of the long-term average direct normal irradiance of the sun indicated that Kano being the study area has high solar direct normal irradiance reaching up to a maximum of 4.8 kWh/m^2.day as shown in Plate I (Solargis, 2017).

Plate I: Nigeria's map of long-term average of direct normal irradiance (Solargis, 2017)

Recent studies have shown that a significant portion of the industrial energy utilization is in a thermal form that can be generated using solar energy technologies. The demand of energy for industrial process heat applications like pasteurization, sterilization, dyeing, etc is one of the main areas for energy consumption which is proportional to the availability of solar radiation during the day. Introducing renewable energies on the industrial sectors could lead to energy savings and mitigation of CO_2 emission. Therefore, solar thermal systems became one of the most attractive solutions for these problems.

The applications of PTSCs are not limited to steam generation for the production of electricity alone but for applications that require temperatures in the range of 70-250°C (Kalogirou, 2013). Many studies were conducted on parabolic trough technology for the generation of thermal energy from solar radiation and highly recommended as a sustainable source of energy for steam production for both domestic and industrial application. Gianluca *et al.* (2015) presented a prototype of a parabolic trough collector with a 90^o rim called UNIVPM.01. Fiberglass was used as the external shell and extruded polystyrene as the inside fill component to reduce heat losses. The aluminium receiver pipe circular section was enveloped using a low-iron glass tube. An electronic tracking device based on a solar-position computer program was used to track the sun. The cost-effectiveness, low weight, high mechanical resistance, and ease of manufacture were among the prototype features. The results show that the intercept and slope of 0.658 and -0.683 were obtained for the equation of thermal efficiency. Mayur *et al.* (2015) investigated the performance of a new parabolic trough collector for hot water generation system through experiments over one full day in winter period at Chandrapur (19.95°N latitude, 79.3°E longitude). A model comprises of the reflector surface, reflector support, absorber pipe and a stand with manual tracking arrangement was fabricated using locally sourced material for rural applications and areas with inadequate electricity supply. The results show that the thermal efficiency and temperature of the working fluid of 32% and 65^{o}C are achieved with the new parabolic trough collector.

Back here in Nigeria, the effort to generate steam using solar technology, a parabolic trough using locally sourced material was constructed and tested under climatic conditions of Dundaye at Sokoto Energy Research Center, Usman Danfodiyo University Sokoto-Nigeria by (Umar *et al.* 2013). The results show that the maximum outlet water temperature of 110°C was achieved. Owoh *et al.* (2015) tested a constructed prototype PTSC under the prevailing condition of Nsukka, Southeast Nigeria. The results depicted that, the maximum efficiency obtained from the test was 44.51% at the ambient temperature of 28ºC and outlet temperature of 102ºC. Sintali (2016) carried out an experimental performance evaluation of a Solar Parabolic-Trough Collector (SPTC) Model TE 38 using solar topocentric coordinates of Bauchi. The results show that solar coordinates have a great influence on the performance of the collector. The maximum hourly temperatures of the glass-cover, absorber-tube and working fluid obtained were 58.3°C, 148.4°C and 132.7°C respectively, while the maximum hourly thermal efficiency of 85.9% was obtained.

This paper presents the experimental study on performance evaluation of the constructed parabolic trough solar collector under the climatic conditions at the new site Department of Mechanical Engineering, Bayero University, Kano-Nigeria (12.05°N, 8.53°E). This is to be carried out using a suitable solar collector test standard and comparing the results with relevant literature.

MATERIALS AND METHODS

Experimental set-up design

The experimental set-up used for the performance evaluation consists of a parabolic trough solar collector, receiver tube, connecting pipes/hoses and valves as shown in Plate II. The details of parts are all discussed.

Plate II: Parabolic trough solar collector

Parabolic trough silvered mirror reflector

According to Thomas and Guven (1993), the accuracy of parabolic shape and its torsional resistance are two factors of concern on the manufacturing of PTSC. These issues are minimized using a metallic frame and making the precise shape of a parabola to a certain extent. A designed parabolic reflector has an aperture width of 1.40 m aperture width and length 2.6 m. The reflector is made-up of mirror strips whose thickness is 1 mm. For the constructing purpose of a concentrator, the horizontal and vertical centerlines were marked on the rectangular cross-section MS sheet plate (2600 mm length, 1610 mm width and 2 mm thickness). The sheet was bent using a rolling machine to produce a parabolic shape until the depth of 350 mm at the horizontal centerline and opening width of 1400 mm were attained. Then a 25.4 mm rectangular square pipe was cut to the dimensions 2600 mm length and 1400 mm width. The 2600 mm and 1400 mm square pipes were welded to form rectangular base support of the trough profile. Also, eight (8) pieces of 25.4 mm rectangular square pipe were cut of different lengths (35 mm, 22 mm, 15 mm and 6 mm) for trough supports. The trough supports were welded at both ends, to parabolic trough and rectangular base support. After that, the mirror strips were pasted on the parabolic MS sheet plate using silicon epoxy gum. The trough is supported by a steel framework. The optical efficiency and geometrical parameters of the PTSC are presented in Table 1.

Table 1: Optical efficiency and geometrical parameters of PTSC

Component description	Unit	Value
Collector length	*m*	2.60
Aperture width	*m*	1.40
Focal length	*m*	0.35
Rim angle	º	90
Glass tube diameter	*m*	0.046
Absorber tube diameter	*m*	0.022
Optical efficiency	-	0.826
Geometrical concentration ratio	-	20

Receiver assembly

The receiver is the key component of a PTSC and its manufacturing requires much attention. It mainly consists of an absorber tube and glass envelope. The optical and thermal performances of collector are affected by the material of the tube and glass cover which reduces heat losses and ensures the protection of receiver. In this prototype, the absorber-tube and the enveloping glass-cover were constructed using a copper tube and borosilicate (Pyrex) glass. The absorber-tube material has an external diameter of 22 mm and a thickness of 1.5 mm and a total length of 2750 mm. The absorber-tube is coated with emulsion black paint that has low emittance thermal property, increases the absorptance of the incident solar irradiance and reduces simultaneously the reflectance. The absorber-tubes are covered concentrically with an enveloping glass-cover of 1300 mm length and were joined together using a brass connector. The enveloping glass-cover material has an external diameter of 46 mm and internal diameter 41 mm. For having an airtight the opening between the glass-cover tube and the absorber-tube, the corks of rubber are provided at the glass tube ends and space was evacuated using a vacuum pump. The internal pressure was assumed to be less than the atmospheric pressure after evacuation. The importance of the glass-tube cover is significant since it reduces heat losses and ensures the protection of the receiver with the tube's coating. A 25.4 mm MS flat plate is rolled to formed support brackets and inserted into threaded rods with a lower nut screwed on top of the three-receiver supports designated at the center and both ends.

Instruments and devices for measurement

For the experimental study, the thermal performance of a PTSC is evaluated, by using different parameters which are recorded with the help of various instruments whose details and their specifications are all discussed. The instruments used are shown in Plate III.

CMP3 pyranometer

The CMP3 pyranometer presented in Plate III (a) was used to measure the diffuse radiation. The instrument manufactured by Kipp and Zonen limited is intended for shortwave global radiation measurements in the spectral range from 300 to 2800nm. The thermopile detector measures irradiance up to 2000W/m^2 with response time <18 seconds and typical sensitivity 10µV/W/m^2 that varies less than 5% from -10ºC to +40ºC. Operating temperature range is -40ºC to +80ºC and stability is better than 1% per year.

Plate III: List of Instruments

Solarimeter

Solar power meter (KM-SPM-11) manufactured by Kusam Electrical Industries was used to measure the instantaneous global radiation. The device is shown in Plate III (b) is capable of taking solar radiation measurement up to a maximum of 1999W/m^2 with a resolution of 1W/m^2 and accuracy of ±10W/m^2.

Anemometer

The Anemometer manufactured by Cussons Technology UK was used to measure the wind speed during the experiment. The instrument possesses the following properties: Range 0.1 m/s – 25 m/s, resolution 0.01 m/s, accuracy air velocity ±5%, temperature ±1ºC and operating temperature up to 50ºC. The Anemometer is shown in Plate III (c).

Digital thermometer

Two DE 305 digital thermometers manufactured by H.K Shah and Company Limited were used in taking the readings of inlet and outlet fluid temperatures in an interval of an hour. The digital thermometer as shown in Plate III (d) is capable of taking temperature measurement up to a maximum of 1300 ºC.

Experimental procedure

A digital compass was used in obtaining the north-south and east-west directions. The parabolic trough collector unit was placed in the sun on a horizontal N-S axis and balanced with the aid of a plum. The reflector surface and receive tube were cleaned to remove dust particles. The receiver was placed along the focal line of the collector as shown in Plate II. A 20L tank was placed little above the height of the collector and connected to the inlet of the receiver tube via a connecting hose. The collector was exposed to the sun at least 30 min before commencement of the experiment. The volume flow rate was measured and recorded by means of a regulating valve, measuring cylinder and a stopwatch. All the connections and components were properly checked before the commencement of the tests. A protractor was fixed on the lower side of the collector with the center side being marked as a reference point against the graduated angles on the protractor and this was used in getting the hourly azimuth angles as shown in Plate IV.

The thermocouples were attached to the inlet and outlet of the absorber tube and the other ends are connected to the DE 305 digital thermometers to measure the temperatures of the inlet and outlet of the working fluid during experimentation. The inlet, outlet temperatures of the working fluid and the beam radiation measured are utilized to evaluate the performance of PTSC.

Plate IV: Incidence angle positioning

Calculation of solar angle

For most solar energy applications, one needs reasonably accurate predictions of where the sun will be in the sky at a given time of day and year. In the Ptolemaic sense, the sun is constrained to move with 2 degrees of freedom on the celestial sphere; therefore, its position with respect to an observer on earth can be fully described by means of two astronomical angles, the solar altitude (α) and the solar azimuth (z). Prior to their definitions the declination and hour angles are needed in determining various relationships.

Solar declination angle

The solar declination is the angular distance of the sun's rays north (or south) of the equator, north declination designated as positive. The angle was obtained by the equation (Kalogirou, 2013):

$$\delta = 23.45° \sin\left[\frac{360}{365}(284 + n)\right] \quad (1)$$

Where: n is the any day of the year.

Hour angle

The hour angle, h, of a point on the earth's surface is defined as the angle through which the earth would turn to bring the meridian of the point directly under the sun. The angle was obtained from the apparent solar time (AST); i.e., the corrected local solar time is

$$h = (AST - 12)15 \quad (2)$$

At local solar noon, AST = 12 and h = 0°.

Solar altitude angle

The solar altitude angle α is the angle between the sun's rays and a horizontal plane. It is related to the solar zenith angle, θ_z which is the angle between the sun's rays and the vertical (Duffie and Beckman 2013):

$$\theta_z + \alpha = \pi/2 = 90° \quad (3)$$

$$\sin(\alpha) = \cos(\theta_z) = \sin(\varphi)\sin(\delta) + \cos(\varphi)\cos(\delta)\cos(h) \quad (4)$$

Where: φ is the local latitude

Solar azimuth angle

The solar azimuth angle, z, is the angle of the sun's rays measured in the horizontal plane from due south (true south) for the Northern Hemisphere (Duffie and Beckman 2013):

$$\sin(z) = \frac{\cos(\delta)\sin(h)}{\cos(\alpha)} \quad (5)$$

Incidence angle

The solar incidence angle θ, is the angle between the sun's rays and the normal on a surface. For a tracking axis oriented in the north-south direction, the incidence is given by the equation (Duffie and Beckman 2013):

$$\cos(\theta) = \sqrt{1 - \cos^2(\delta)\cos^2(h)} \quad (6)$$

Meteorological data

The hourly global and diffuse radiations were obtained using Solarimeter and Pyranometer respectively while the hourly wind speed and ambient temperature were obtained using Anemometer. The inlet and outlet temperatures were recorded using Digital thermometers. The values recorded were used in computing the useful heat gain and thermal efficiency of the PTSC.

Performance of PTSC

Optical performance of PTSC

Most previous studies have assumed the uniformity of the heat flux received around the heat collection element (HCE). However, in reality the heat flux is non-uniform and not all the solar energy incident on the collector is reflected back to the HCE due to imperfections of the reflector causing some optical losses. The optical efficiency relies on many factors such as tracking error, geometrical error, and surface imperfections. With modern computational tools available accurate determination of heat flux around the HCE is possible. The

Monte Carlos ray-tracing technique was employed for the determination of optical efficiency using SolTrace. The optical efficiency and geometrical properties used for the optical simulation are presented in Table 2. The detailed optical performance study is not presented in this paper.

Thermal performance of PTSC

The performance evaluation was conducted to determine the useful heat gain, thermal instantaneous efficiency and thermal efficiency of the PTSC

Useful energy

The useful heat energy from the collector was obtained by using the equation

$$Q_u = \dot{m}c_p\left(T_{fo} - T_{fi}\right) \tag{7}$$

Where: $\dot{m}$ is the mass flow rate, the specific heat c_p of the working fluid (water) is based on its average temperature through the receiver and calculated from the equation given by Kroger as cited in Brook *et al.* 2006, T_{fi} and T_{fo} are the inlet and outlet temperature of the working fluid.

$$c_p = 8.15599 * 10^3 - 2.80627 * 10(T_{ave}) + 5.11283 * 10^{-2}(T_{ave})^2 - 2.17582 * 10^{-13}(T_{ave})^6 \tag{8}$$

Where: T_{ave} is the average temperature of the inlet and outlet $\left(\frac{T_{fi}+T_{fo}}{2}\right)$

Thermal instantaneous efficiency

The useful energy, beam radiation and the aperture area were applied to equation (9) to obtain the thermal efficiency (Ma *et al.* 2010):

$$\eta_{th} = \frac{\dot{m}c_p(T_{fo}-T_{fi})}{G_b A_a} \tag{9}$$

Where: G_b and A_a is the beam radiation falling on the concentrator and aperture area of the collector respectively,

Thermal collector efficiency

Under a steady state conditions the thermal collector efficiency of collector through the First Law is given as (Kalogirou, 2013):

$$\eta = F_R\left[\eta_o - U_L\left(\frac{T_{fi}-T_a}{CG_b}\right)\right] \tag{10}$$

Where $C = W_a/\pi D_{ao}$ the concentration ratio, W_a the aperture width, D_{ao} the outer diameter of absorber tube, T_a the ambient temperature.This equation has the form general equation of $y = b + mx$, which experimentally used to obtained the heat removal factor F_R and the overall heat loss coefficient U_L (Kalogirou, 2013). Linear models of thermal efficiency described by (Duffie and Beckman 2013) were imposed on the experimental data according to Equation (10), where $F_R U_L/C$ is the slope of the line and $F_R\eta_o$ is the y-intercept. Therefore, Equation (10) plots as a straight line on a graph of efficiency versus the heat loss parameter $\left(\frac{T_{fi}-T_a}{G_b}\right)$.

RESULTS AND DISCUSSION

Effect of beam radiation on the temperature difference of a PTSC receiver

The experiment was conducted between 0900 hours to 1700 hours of selected days for the months of October, November, 2018 and February, March, April and May 2019. Late October and early November in 2018 are characterized as hot season time with high sunshine in Kano and its environs. The measured hourly data for the clear sky of ambient, inlet and outlet temperatures, global and diffuse radiations and wind speed for each month were taken and recorded. The effects of collector inlet temperature and ambient conditions on PTC system were investigated. Figure 1 shows the experimental temperatures of the inlet and outlet of the working fluid of the PTSC as obtained hourly during the experiment. The lowest and highest inlet temperatures of the working fluid recorded during the test period were 27.5 ºC and 41.8 ºC at 09.00 hours and 13.00 hours in the months of November and April respectively. The outlet temperature increased with time and the maximum recorded was 133.5°C in the month of April 2019. The lowest and the highest outlet temperatures of the working fluid recorded during the test period were 56.2 ºC and 133.5 ºC at 09.00 hours and 13.00 hours in the months of October, 2018 and April, 2019 respectively. It can be seen from such figure that, the increase in the inlet and outlet water temperatures continues to rise from morning until it reaches noon where it falls to the end of the experiments. This phenomenon can be attributed to the fact that the received solar radiation falls directly on the collector due to continuous manual tracking of the sun for maximum collection.

Moreover, it can be seen in Figure 2 as the solar radiation increases, the temperature difference through the collector increases, for example, with the flow rate of 0.0042 kg/s, the highest temperatures difference was in the range 66.3°C - 92.5°C and occurred mostly at noon, while, the lowest temperatures difference was in the range 27.8°C - 64.3°C and observed mostly at the start of the experiment. The beam radiation increased with time until around 1300 hours when it declined and the maximum beam radiation recorded was 841 W/m^2 in the months of April and March, 2019. A linear correlation equation with a R^2 value of 0.965 was obtained as shown in Figure 3.

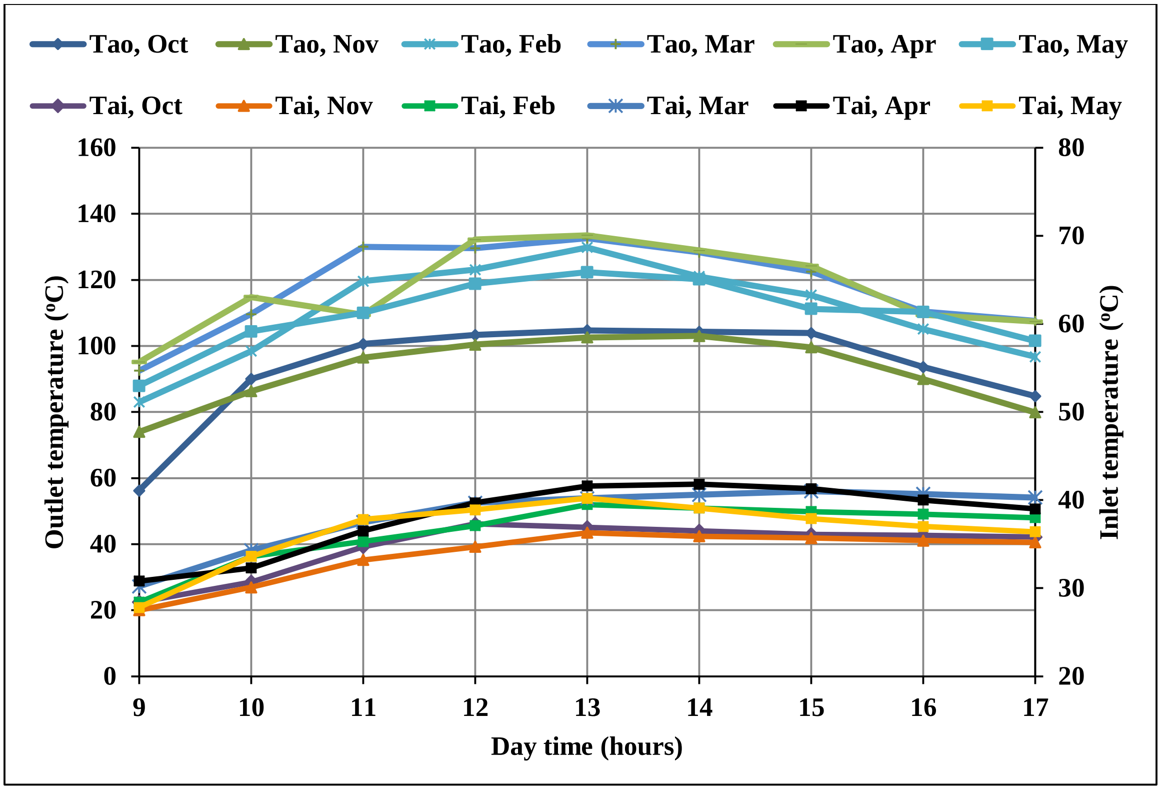

Fig. 1:Variation of inlet and outlet temperature of the PTSC receiver

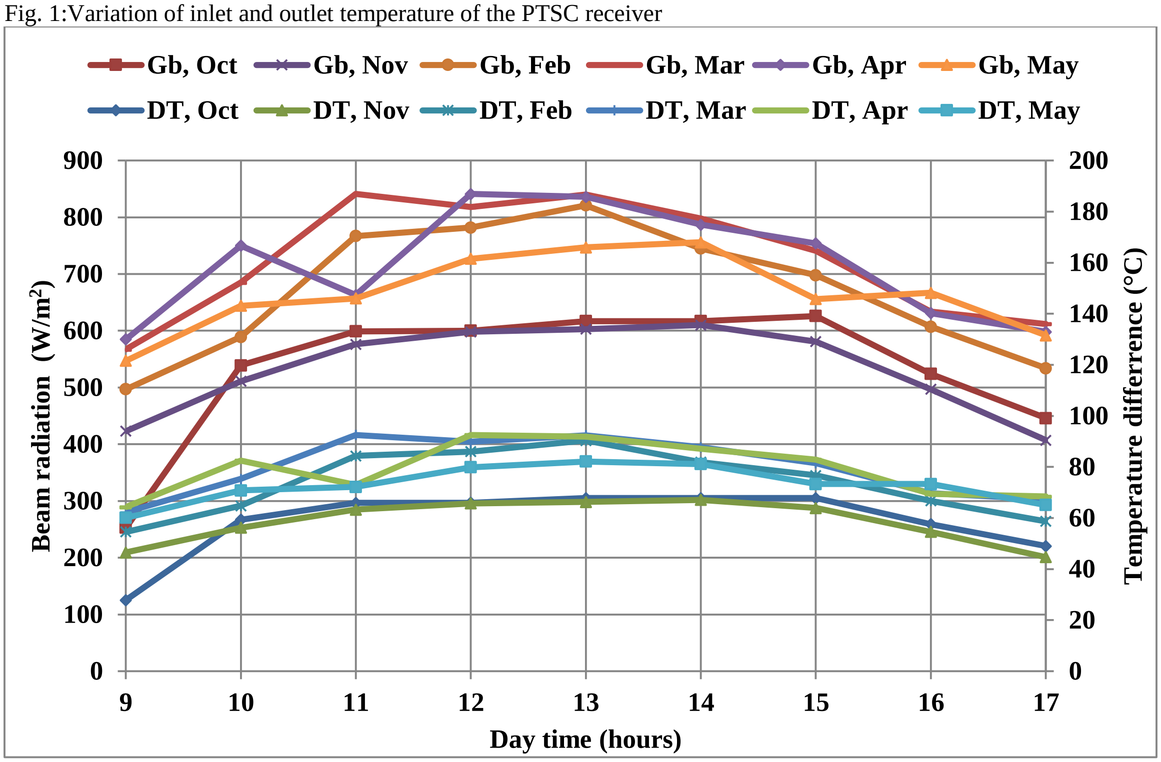

Fig. 2: Variation of temperature difference and beam radiation on PTSC receiver

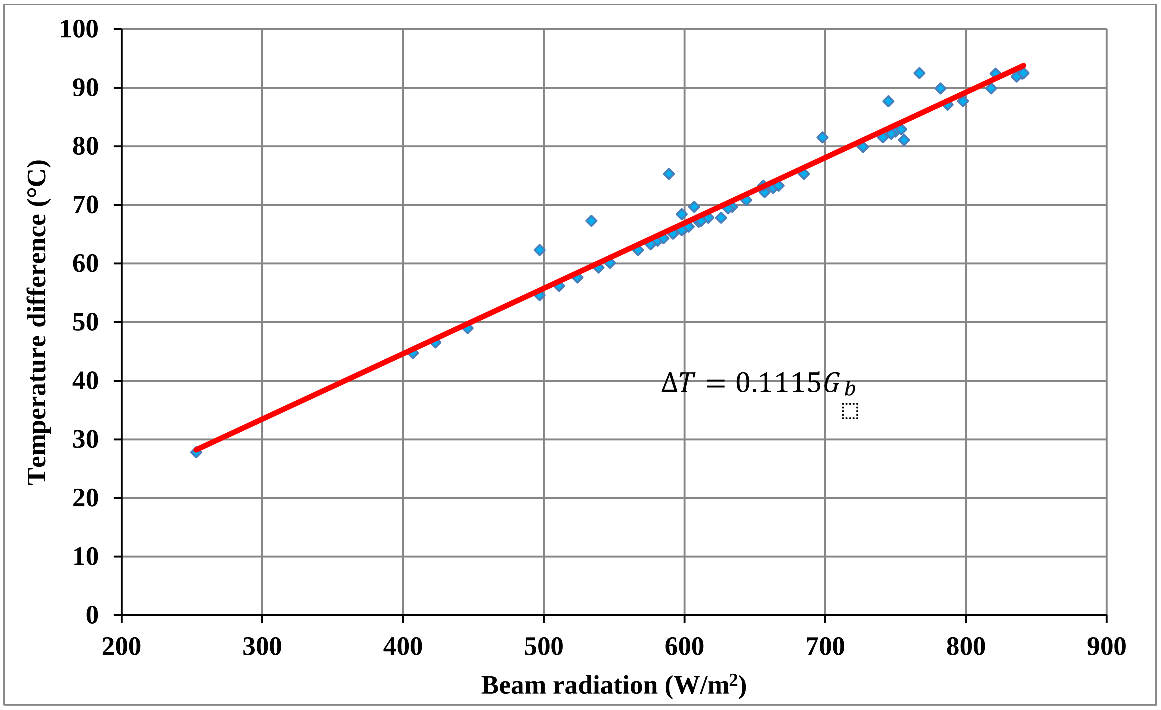

Fig. 3**:** Variation of temperature difference and beam radiation on PTSC receiver

Useful heat gain and thermal efficiency

The data recorded of the beam radiation, the inlet and outlet temperatures were collected for different days under similar weather conditions at the same flow rate. Figure 4 shows the relation between the variation of the useful heat gain and beam radiation. The lowest and the useful heat gain by the working fluid during the test period were recorded as 0.488 kW and 1.64 kW at 09.00 hours and 13.00 hours in the months of October and April respectively.

It can be seen from such figure that, the useful energy of the collector first starts to increase as the solar radiation increases until it reaches a maximum value around noon and then starts to decrease slowly as the time passes due to decrease in solar radiation. Thus, the useful heat gain increase with the increase of solar radiation, and it was as a result of the temperature difference between the fluid and the contact surface causes density variation in the fluid, convective heat transfer takes place and thus heat is being transferred from the tube to the fluid. The rate at which heat was actively removed from the absorber-tube to the fluid determines the operating temperature of the collector.

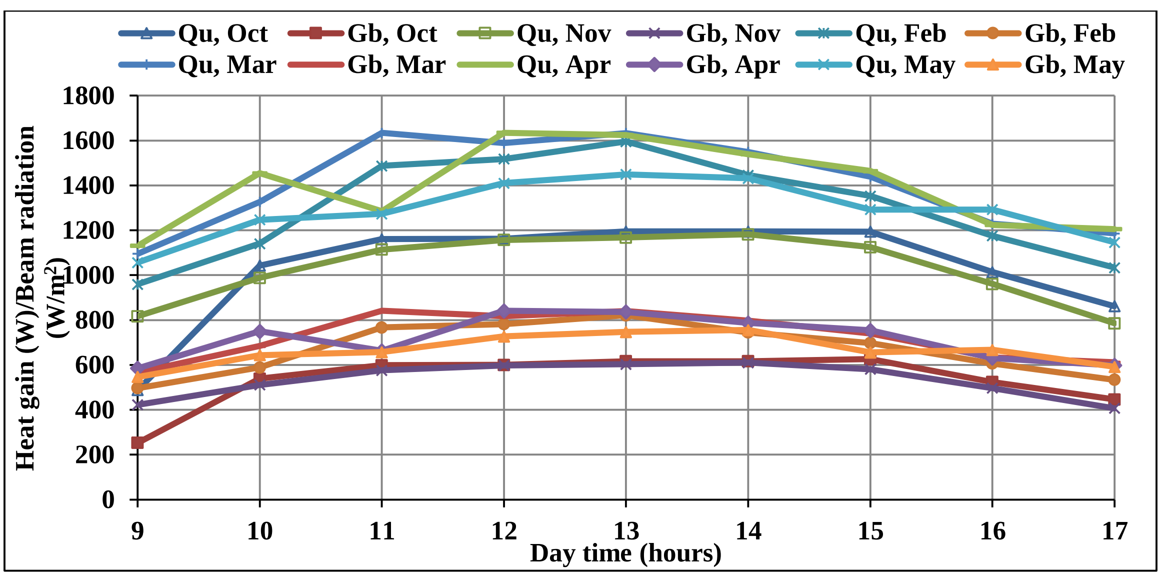

Fig. 3: Variation of useful heat gain and beam radiation

Thermal collector efficiency

The thermal efficiency curve of the PTSC of the present work was derived from a series of test points at a flow rate of 0.0042 kg/s that passes through the receiver.

Equation (10) plots as a straight line on a graph of efficiency versus the heat loss parameter $\left(\frac{T_{fi}-T_a}{G_b}\right)$.

The efficiency curve for the system at the flow rate of 0.0042 kg/s is shown in Figure 4, and the points show the thermal instantaneous efficiency and a straight line of best fit can be drawn between those points to obtain the thermal efficiency for the collector, and a peak value of 53.2% for the thermal collector efficiency was obtained for the receiver.

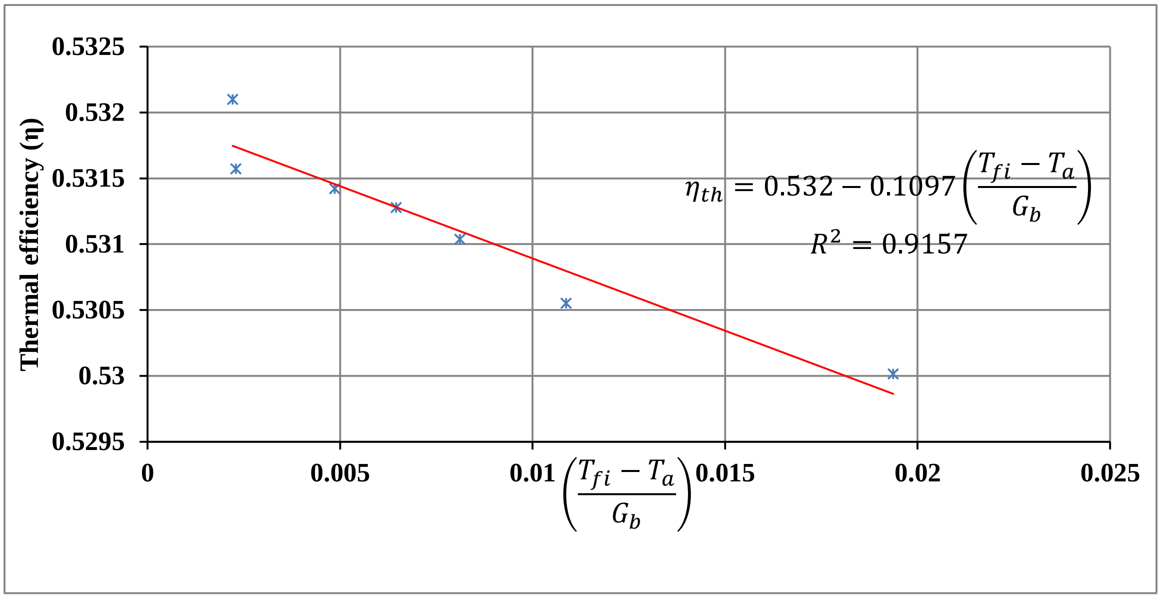

Fig. 4: Thermal efficiency curve of the PTSC

It is noted clearly, that the collector efficiency is at the high-temperature difference and this phenomenon can be attributed to the fact that higher heat gained and absorbed at a higher temperature difference. The intercept of the line describes the $F_R\eta_o$ and was found to be 0.532, with geometric concentration C of 20, the F_RU_L was found to be 2.194 W/m^{2}K, and the optical efficiency η_o of 0.826 obtained from optical performance study was employed, and the heat removal factor F_R and overall heat loss coefficient U_L were found to be 0.6441 and 3.406 W/m^{2}K respectively. While Table 3 shows the efficiency curves equations that have been reported in the literature for this type of solar collectors.

Table 2: Thermal Efficiency for different types of PTSC

S/No	Equation of PTSC curves	References
1	$\eta_{th} = 0.543 - 0.189\left(\frac{T_{fi}-T_a}{G_b}\right)$	Hau and Soberanis 2011
2	$\eta_{th} = 0.5214 - 0.1006\left(\frac{T_{fi}-T_a}{G_b}\right)$	Yilmaz *et al.* 2015
3	$\eta_{th} = 0.532 - 0.1097\left(\frac{T_{fi}-T_a}{G_b}\right)$	Present work

CONCLUSION

The PTSC was evaluated at a constant flow rate of 0.0042 kg/s for some selected days, where the operation of the system took place from 0900 to 1700 hours. The maximum temperature recorded was 133.5 °C and occurred in the month of April 2019. The thermal performance of PTSC was evaluated and the efficiency curve for the PTSC was estimated. Peak efficiency of 53.2% was obtained for the PTSC with a constant flow rate at a higher temperature difference of 92.5°C. The collector efficiency equation obtained in the present study compares well with the other reported literature. In general, the attained efficiency and temperature are fairly acceptable and to my knowledge, it is the first attempt to fabricate such type of collector locally and evaluated in Kano-Nigeria environment. The results of the maximum outlet temperature of 133.5°C recorded in this work establish the technical feasibility of using PTSC for industrial process heat applications.

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