EXPERIMENTAL DESIGN AND DEVELOPMENT OF LOCALLY MADE PARABOLIC TROUGH SOLAR THERMAL COLLECTOR UNIT

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ABSTRACT

The design and analysis of Parabolic Trough Solar Thermal Collector (PTSTC) system used to generate hot/steam water for domestic and industrial purposes were carried out. The parametric studies were also conducted on the collector, study the effectiveness of hot water production for potential applications. The PTSC was designed with Parabolic Software version 2.0. The fabrication and design were done with a combination of reflector surface, reflector support, absorber pipe and wooden stand. The absorber pipe was painted in black colour while the trough was manually operated. The flow of water in the system follows the recycling process repeated during data acquisition. The ambient temperature, the inlet and outlet temperature of the receiver and total solar radiation on the PTSC were recorded. Different flow rate of the Heat Transfer Fluid (HTF) was tested at 0.021, 0.022, 0.023 and 0.024 kg/s respectively. Collected data showed the maximum outlet water temperature attained as 72^{o}C. The average outlet temperature increased from 36^{o}C at 10:30 hour to 69.84^{o}C at 16:00 hour. The average beam radiation during the collection period was 699 W/m^2. Different flow rates show that the lower the flow rate, the higher the efficiency of the system. The study revealed that the developed parabolic trough solar collector is viable for the production of sterilized water and low stage steam for domestic and industrial purposes.

Keywords: *Parabolic trough collector, Beam radiation, Efficiency, Reflector surface, Flow rate*

Introduction

Solar energy is the energy directly from the sun which is one of the most important non-conventional energy sources available for man's use. It is a clean, renewable and free source of energy largely available in sufficient quantity. Man can harness the energy for useful purposes by means of active and passive devices among which are solar cells, photothermal converters, concentrators, flat plate collectors as well as solar architecture. Devices such as photothermal converter produce high temperature and pressure which can be used to generate electricity. Solar cells are used to convert solar radiation to direct current (d.c) current [1]. While, Solar collectors are a form of heat exchanger that converts solar energy into heat and transfers it to a fluid (usually air, water, or steam) flowing through the collector [2]. Solar collectors (both concentrating and non-concentrating) are used for domestic and industrial water heating purposes [3, 4]. The parabolic trough collector (PTC), linear Fresnel reflector, solar dish, and solar tower are the most popular concentrating technologies [5], with the parabolic trough collector being one of the most well-known [6]. The incident radiation is focused onto a receiver tube that is positioned at the focal line of the trough using parabolic shaped reflectors [7,8]. The advantages of the parabolic trough collector (PTC) can be seen in industrial steam generation [9] and hot water processing [10]. Solar troughs also, have the advantages of being safe, inexpensive, and capable of supplying thermal energy.

However, the amount of useful solar energy trapped is influenced by many factors such as location of site, type of collector, solar irradiation, sunshine hours, radiation intensity and relative humidity etc. J. Ramesh and his colleagues built a solar water heater out of the workshop's materials (plywood, reflective aluminum panel, storage tanks, and copper tube). They looked at total direct radiation on the collector's plane, ambient temperature, wind speed, water flow rate, and the inlet and outlet temperatures of the water within the absorber tube to see how well the solar parabolic trough collector performed. They discovered that the increase in heat gain is dependent on time and solar intensity [11]. More so, the type of collector to be used in a particular application depends on the temperature at which energy is to be delivered, as well as the cost envisaged [3]. Pradeep Kumar et al., described a low-cost method for mass fabricating PTC with its automated sun tracker, Pradeep Kumar K V et al. identified a low-cost method for mass production of PTC. They investigated various types of absorbing materials in order to improve the solar concentrator's efficiency, as well as the optical properties and degradation of the reflecting surfaces [8].

There are numerous literature studies that examine the efficiency of a parabolic trough collector, according to the above-mentioned literature review. However, there is little or no report on studies of the thermal efficiency of a collector fabricated with locally sourced materials. As a result, this research present low-cost solar water heater. Solar radiation, inlet and outlet water temperature, flow rate, and performance were all estimated for optimum performance.

Materials and Methods

Location and Size of the Study Area

A parabolic trough solar collector model was developed and installed in the open area of the Chemical Engineering Department, Obafemi Awolowo University, Ile-Ife, Osun State, Nigeria. The location is latitude of 7.4667° North, longitude of 4.5667°East. The City boasts of a population of about 356,694 people, based on the 1991 Census and the postal code of the area is 230.

Research Design

The designed consists of a wooden support frame, galvanized sheet, reflector sheet, solar radiation absorbing system (stainless pipe) and driving system. Each heater section uses half of a standard four foot by eight-foot galvanized sheet. The parabolic trough collector uses reflector surfaces that linearly extend into a trough shape.

Parabolic Trough Collector Design

The dimension of curved sheet for parabolic trough module was 2.44 m length and 0.61 m aperture width with effective aperture area of 1.49 m^2.

The collector was designed with simple parabolic expression given in equation (2.1) and the reflector was designed to set the focal length ($f = 0.11479\,m$) from the vertex (V) and the aperture width of the system ($W = 0.56\,m$) using Cartesian equation as design system reported by Eltahir and Mohamed, 2013).

$$x^2 = 4fy \tag{2.1}$$

From equation (2.1), the height of the parabola in terms of the focal length and aperture diameter is:

$$\left(\frac{w}{2}\right)^2 = 4fh_c \tag{2.2}$$

The rim angle ψ_{rim} is given by:

$$Tan\,\frac{\Psi_{rim}}{2} = \frac{w}{4f} \tag{2.3}$$

According to (Egbo *et el.*, 2008) the arc length of the parabolic curve, S_p was computed using equation (2.4):

$$S_p = \left[\frac{w}{2}\sqrt{\left[\frac{4h_c}{w}\right]^2 + 1}\right] + 2fIn\left[\frac{4h_c}{w} + \sqrt{\left[\frac{4h_c}{w}\right]^2 + 1}\right] \tag{2.4}$$

However, the arc length (S_p) was found to be 1m and used to determine the reflective surface area, A_s, by equation (2.5).

$$A_s = S_p\,.\,L \tag{2.5}$$

The rim angle θ_R, corresponds to beam radiation reflected from the outer rim of the concentrator, calculated with equation (1.6) as reported earlier (Egbo *et al.*, 2008).

$$\theta_R = \cos^{-1}\left[\frac{2f}{[(0.5w)^2 + (f - h_c)^2]^{½}} - 1\right] = \cos^{-1}\left[\frac{2f}{R} - 1\right] \tag{2.6}$$

Parabolic Trough Collector Size

The sheet was curved to form a parabolic trough module of 2.44 m length and 0.61 m aperture width with effective aperture area of 1.49 m^2. The focal point estimation of the parabolic trough solar collector was calculated using parabola calculator version 2.0 at specified diameter and depth of the parabola. The total numbers of parabolic trough solar collector to produce are four sections as shown in Figure 1. The values of the aperture area, curve surface area, the focal length, height of the parabola, the aperture width, the receiver outside diameter and the length of the concentrator were calculated from equation (2.1) and (2.6). The total collector surface consists of one reflector sheet of $1.49\,m^2$ $(0.61\,m \times 2.44\,m)$.

Principle of Operation

The experimental setup used for testing the PTSC consists of the constructed collector, 25 liters storage tank and throttling valve. The principle adopted in the construction was parabolic reflecting surface principle, which takes the advantage of all parallel rays of light from the sun that incident on a parabolic shaped mirror and converge after reflection to a point focus.

The storage tank is fixed above the receiver's pipe level to allow the heating fluid to flow naturally without pumping system. The storage tank is filled with water from the main supply through an open flow system. The force is used to circulate water from the collecting tank through the absorber tube of the solar collector back to the collecting tank. The water temperatures at the inlet and outlet of the absorber tube, ambient temperature, mass flow rate, and solar radiation intensity are continuously measured during the experiment.

Method of Data Collection

The hot water flowed into a container and transferred back into the storage tank above the parabolic trough through recycle process technique. In the experiment, the effect of water flow rate, recycling process and solar tracking was determined. The tracking of the solar intensity was done manually. The determination of the temperature difference at the temperature inlet and outlet of each node was taken at regular intervals of 30 minutes throughout the experiment period. Data obtained was subjected to appropriate descriptive and inferential statistics.

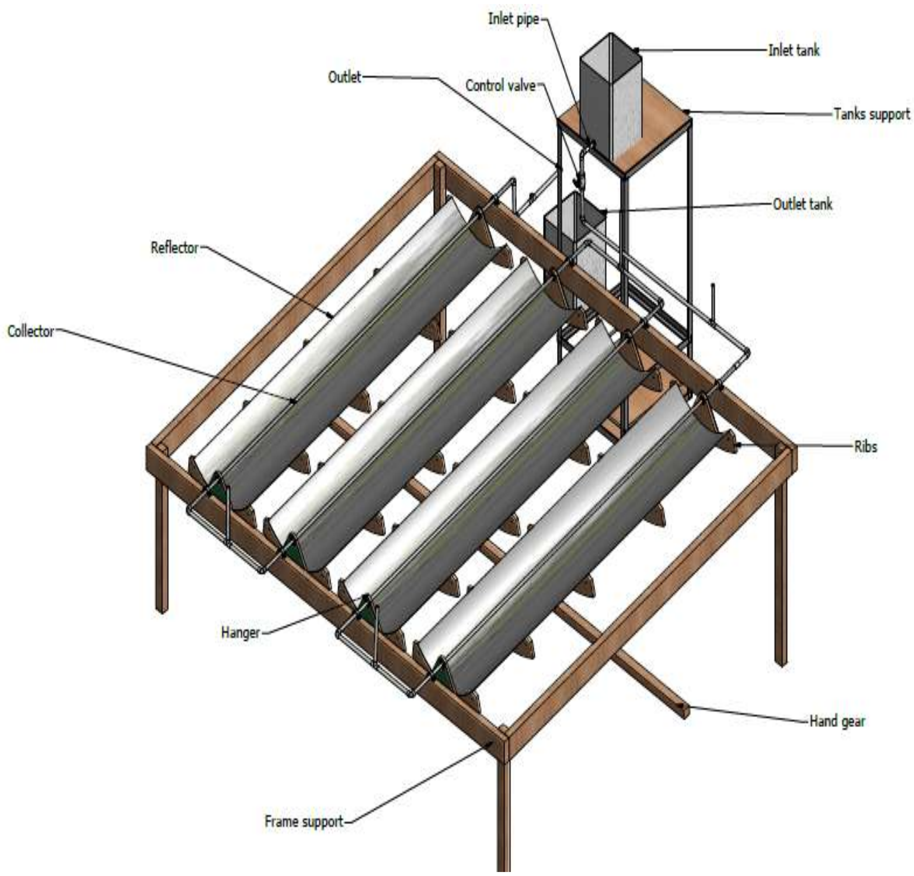

Figure 1 Schematic Diagram of the Designed and Fabricated (PTSC)

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Results and Discussion

The calculated values of the aperture area, curve surface area, the focal length, height of the parabola, the aperture width, the receiver outside diameter and the length of the concentrator of the fabrication shown in Table 1. The collector height h_c is almost equal to the focal length f.

Table 1 Parabolic Trough Collector System Specifications

Parameter	**Sample**	**Value**
Length	L	$2.4\ m$
Aperture Area	A_s	$1.49\ m^2$
Curved Area	A_s	$1.3655\ m^2$
Focal Length	f	$0.11479\ m$
Receiver diameter	d	$19\ mm$
Width	W	$0.61\ m$
Height	h_c	$0.110\ m$

Geometry Analysis of the PTSC

Measurements of the PTSC were taken and calculations made to get the dimensions of the trough. The trough is considered to be that of a parabolic concentrator with aperture width (W) of 0.56 m and a depth (h_c) of 0.110 m. The specified results for the focal length (f), the parabolic radius of curvature (R), the height of the parabolic curve (h_c) and the arc length of the parabolic curve (S_p) of PTSC for the following rim angles are 15°, 30°, 45°, 60°, 75°, 90°, 115°, 150° were achieved respectively.

Figure 2 shows the effect of various rim angles on the geometric dimensions of PTSC. As the rim angle increases the focal length decreases. The radius of curvature and the rim angle have parabolic relationship, as the parabolic radius decreases the rim angle increases. However, at rim angle of 90°, it was slightly steady before increase progressively within the investigation ranges of 150°. From the rim angle of 15° to 100°, there was steady increase of arc length but it was observed that a rapid increase in arc length within the rim angle of 150°. The height of the curve increases steadily with increase in rim angle and there was a rapid increase in height ranges between the rim angles of 100° to 150°.

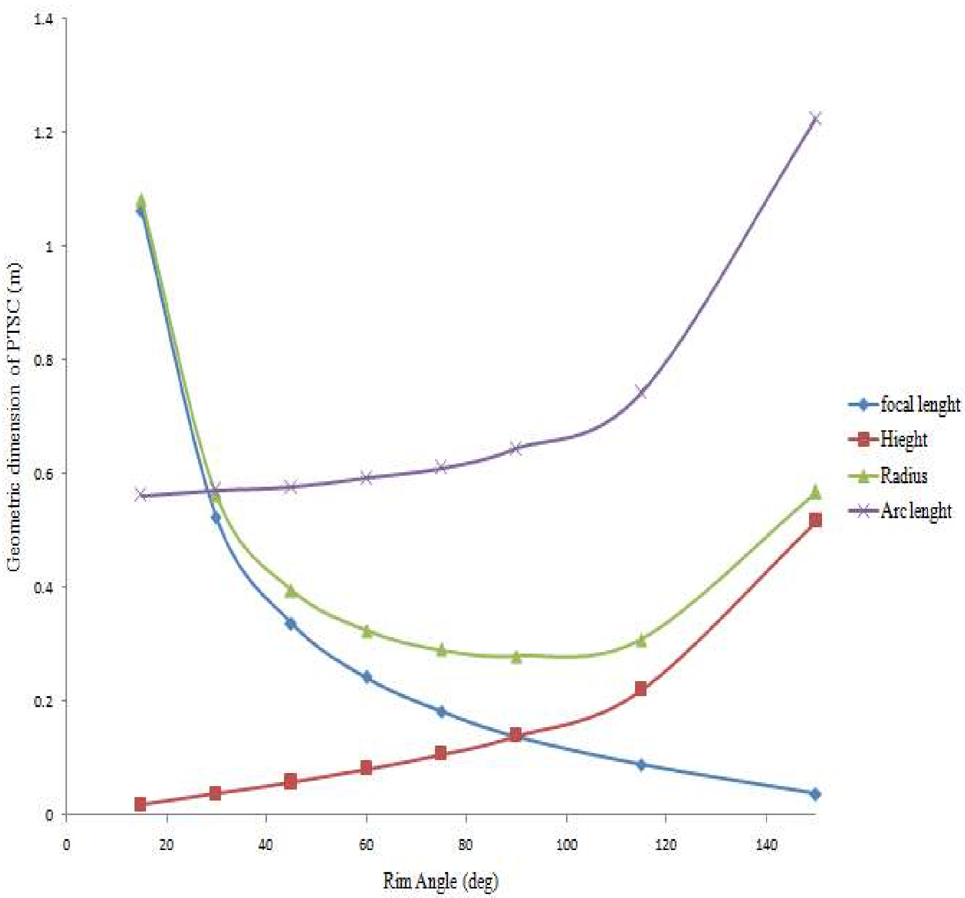

Figure 2: Geometric dimension of a PTSC versus rim angle with common aperture width 0.56 m.

Total Solar Radiation and Time

The performance of the fabricated PTSC was optimum in the afternoon between 12:00 pm and 1:00 pm, when the solar radiation was hotter than the morning hours. The optimum temperature was 72°C and 55% thermal efficiency was obtained.

At solar noon, the total solar radiation falling on the PTSC was measured to be approximately 725 W/m^2. The beam solar radiation was measured to be approximately 511 W/m^2 as shown in Figure 3.

The total radiation and beam radiation vary within the interval of 10:30 am and 12:00 pm as time increases and slightly steady between 12:00 pm and 12:30 pm before it started decreases between 12:30 pm and 4:00 pm as the time also increases. The reason for changes in the variation may be due to variation in weather condition.

Also, the value of each of those parameters was observed to be at peak around noon when the incident beam radiation was maximum. The results also showed that the efficiency of PTSC decreased for various mass flow rates and Heat Transfer Fluid (HTF) as the inlet fluid temperature increases. This was because the radiation losses increase as the collector temperature increases.

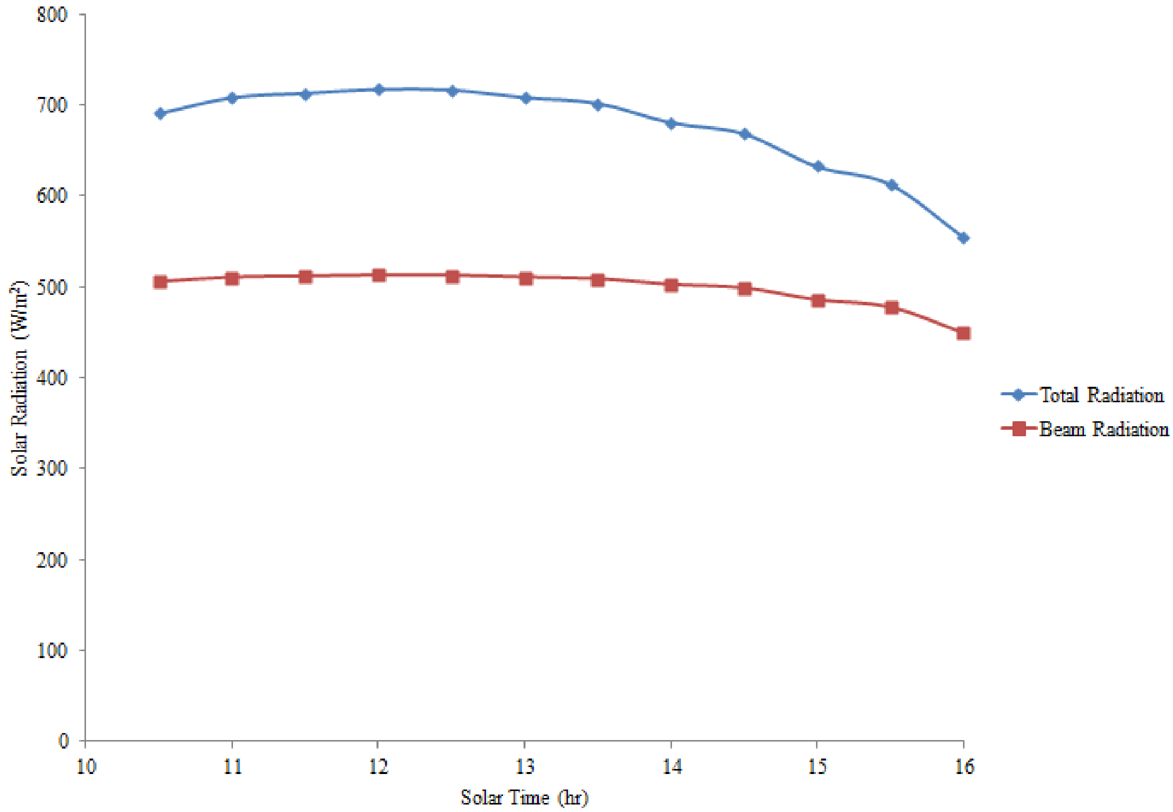

Figure 3: Variation of Solar Radiation (Total and Beam) Versus Solar Time.

Total Solar Radiation and Temperature for a Coated Metallic Receiver

A period of four clear sky days (11th and 18thJanuary, 2014) and (15th and 16th February, 2014) have been selected for measuring all necessary data for the analysis of the performance of the PTSC by using coated metallic receiver. A plot of temperature against time obtained on these days are shown in Figures 4.4a and 4.4b where the ambient temperature, the inlet and outlet temperature of the receiver and total solar radiation on the PTSC are shown in which the flow rate of the Heat Transfer Fluid (HTF) is 0.021, 0.022, 0.023 and 0.024 kg/s respectively.

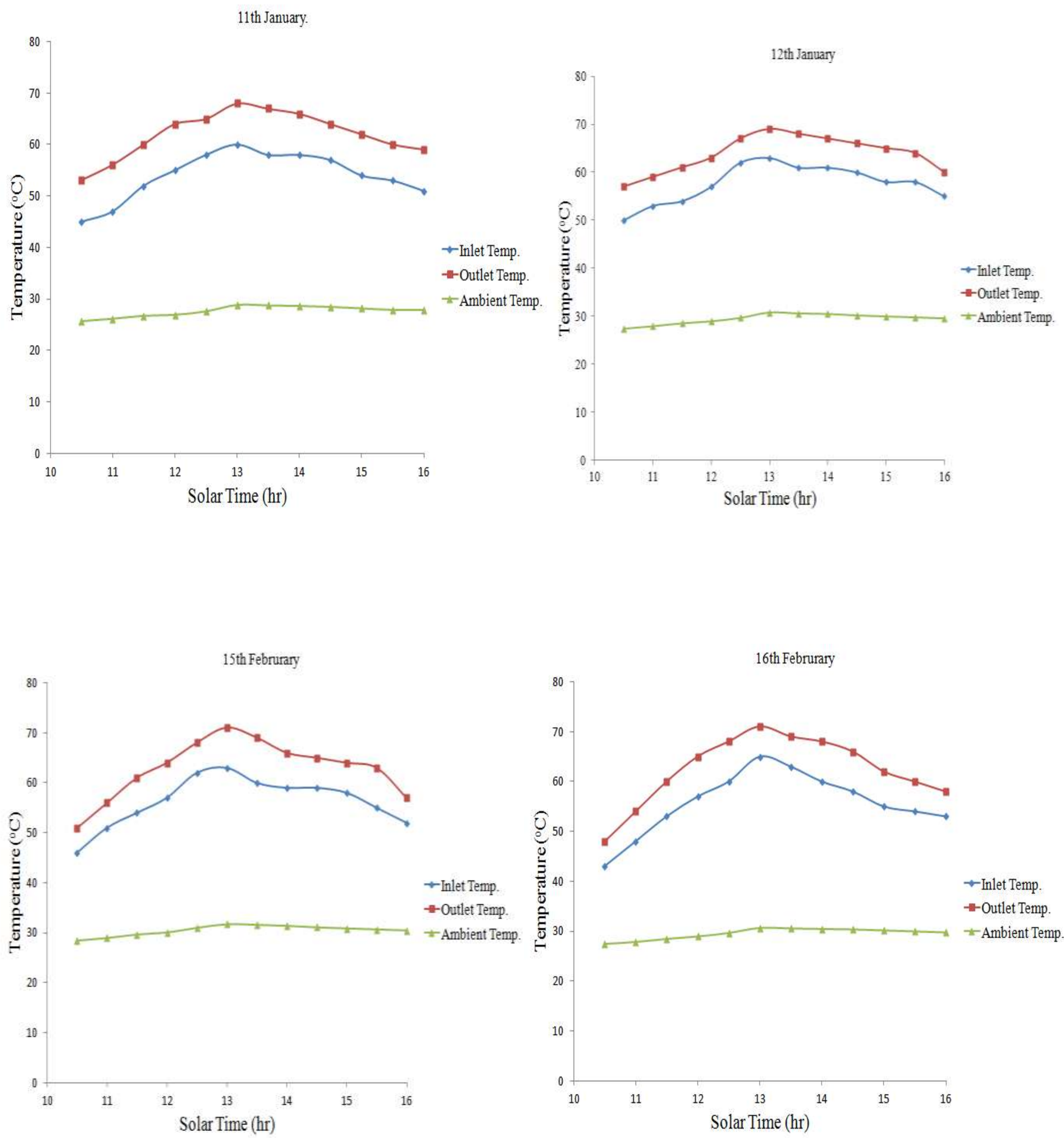

Figure 4.4a Variation of ambient temperature, inlet and outlet temperature of a coated metallic receiver with local time for different clear January and February days.

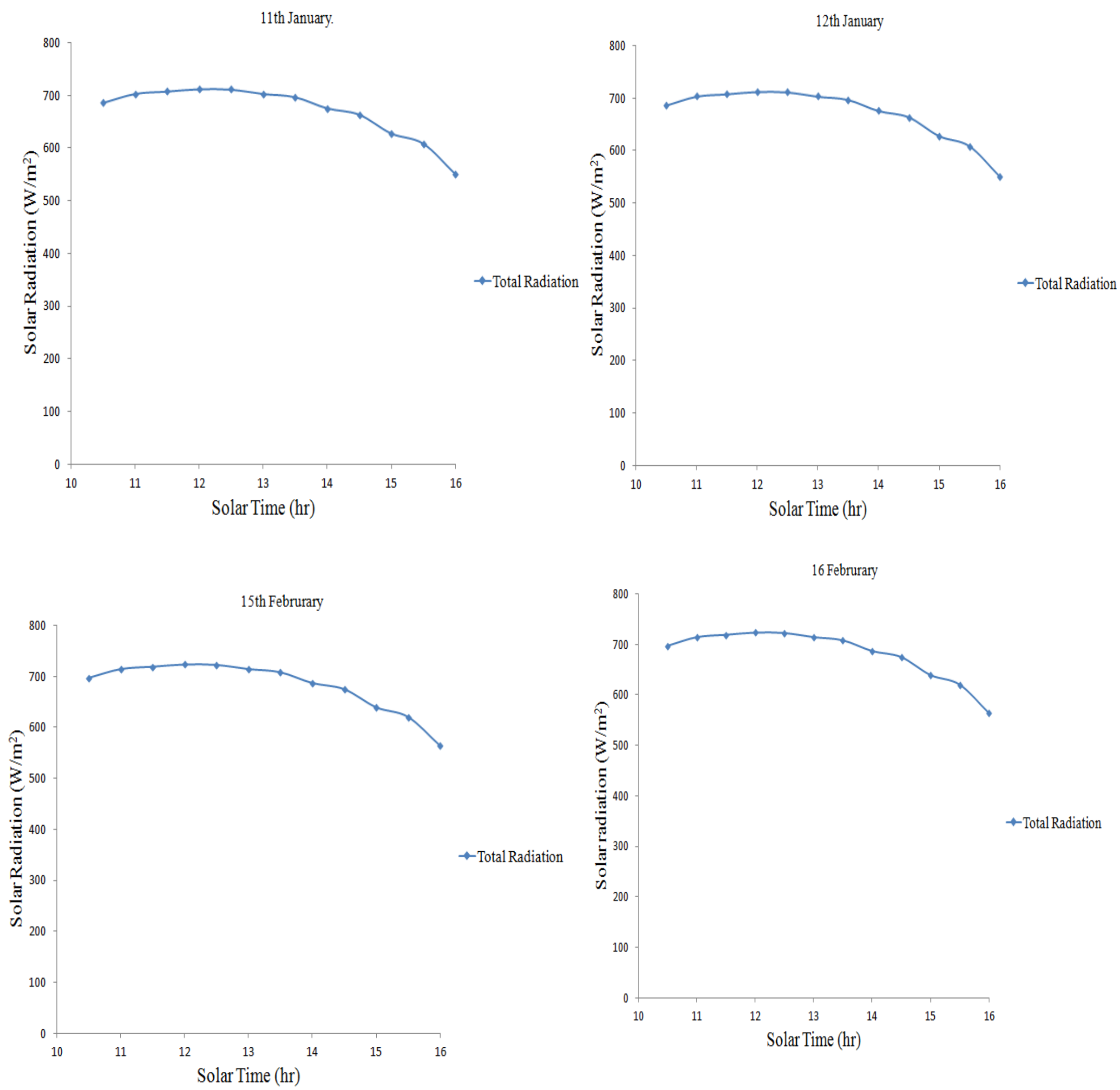

Figure 4.4b Variation of total solar radiation of a coated metallic receiver with local time for different clear January and February days

Higher temperatures were observed during the day time occurring between 12:30 pm and 1:30 pm with a peak occurring at about 1:00 pm. The total solar radiation was also measured during the test period and higher value of total solar radiation was observed between 11:30 am and 12:30 pm with a peak occurring at about 12 noon.

An increase in outlet HTF temperature was noticed during early hour of the day until it reaches maximum value around mid-noon when total solar radiation value is the highest. The experiment was conducted from 10:30 am to 4:00 pm with a total solar radiation in the range of 563 W/m^2 to 723 W/m^2 and ambient temperature in the range of 29 to 32^{o}C. After that, outlet HTF temperature inside the receiver reached 72^{o}C in clear February day where the maximum registered ambient temperature was 32.2^{o}C. It was noticed that the HTF temperature inside the receiver increased when the ambient temperatures were higher or when the solar intensity is abundant.

The temperature of the fluid in storage tank was raised by convection. The rising is proportional to that of incident solar radiation until solar noon when the temperature of storage tank leaves the storage to the inlet of the receiver. This rising can be attributed to the selective surface (special black paint) for the receiver which is a combination of high absorptance for solar radiation with a low emittance for the temperature range in which the surface emits radiation.

Temperature was continuously increasing due to the fact that the temperature of HTF in storage tank is directly proportional to useful heat energy. This energy was increases continuously with time whenever the solar radiation is available. Analyzing Figure 4.4a for 16th February, it can be found that the outlet HTF temperature and storage temperature increase from 35 to 71°C and from 31 to 48°C. The solar radiation intensity and local time are varied from 564 to 724 W/m^2 and from 10:30 am to 4:00 pm. Therefore, at any instant, the receiver HTF temperature is greater than the storage tank fluid temperature. The big difference in performance can be attributed to using special black paint receiver.

4. Conclusion

The operating performance of the locally fabricated parabolic trough solar power plants has demonstrated it technology ability to be robust and excellent performer in the commercial power industry. the optimum outlet water temperature of 72°C and 55% thermal efficiency obtained from PTSC plant shows that the solar thermal power can compete well with conventional fossil fuel and renewable energy power plants in the energy market. Different flow rates show that the lower the flow rate, the higher the efficiency of the system.

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References

Adeoye A. E., Ajenifuja E., Alayande S.O., Ogunmola E. D., and Fasasi A. Y., Effect of Zn doping concentration on optical and photovoltaic performance properties of Zn-PbS Thin Film Solar Cell, *SN Applied Sciences*, 20202:1560, DOI10.1007/s42452-020-03348-z

Kalogirou S. A.. Solar Thermal Collectors and Applications *J. Progress in Energy and Combustion Science*, 2004, 30: 231-295. DOI: 10.1016/j.pecs.2004.02.001

Adeaga, Oyetunde Adeoye, Dare, Ademola Adebukola and Raji, Fatai Olasunkanmi (2017). Potentials of Industrial Solar Drying of Agricultural Produce. *International Journal of Science and Technology*, 3 (7)

Tian Y. and Zhao C.Y.. A Review of Solar Collectors and Thermal Energy Storage in Solar Thermal Applications *J. Applied Energy*, 2013, 104: 538–553. DOI: 10.1016/j.apenergy.2012.11.051

Selvakumar Nagarajan, Harish Barshilia and K. S. Rajam (2010). Review of sputter deposited mid to high-temperature solar selective coatings for Flat Plate/Evacuated tube collectors and solar thermal power generation applications

Bellos E. and Tzivanidis C. Analytical Expression of Parabolic Trough Solar Collector Performance *J. Designs*, 2018, 2(9): 1-17. DOI: 10.3390/designs2010009

Tayade M. G., Thombre R. E. and Dutt S.. Performance Evaluation of Solar Parabolic Trough *J. International Journal of Scientific and Research Publications,* 2015, 5(1): 1-5.

Kumar P. K. V., Srinath T. and Reddy V.. Design, Fabrication and Experimental Testing of Solar Parabolic Trough Collectors with Automated Tracking Mechanism *J. International Journal of Research in Aeronautical and Mechanical Engineering*, 2013, 1(4): 37-55.

Qu W., Wang R., Hong H., Sun J. and Jin H.. Test of a solar parabolic trough collector with rotatable axis tracking *J. Appl. Energy*, 2017, 207: 7–17. DOI: 10.1016/j.apenergy.2017.05.114

Dare A. A, Odunfa K. M., Ajuka L. O., Oyedepo S. O., Adeaga O. A., Estimation of insolation of flat plate solar collectors in selected cities in Nigeria, 2017 *International Journal of Computational Engineering Research, 7(12): 15-28*

Ramesh J., Kumar J. K. and Subbareddy D. E. V.. Design, Fabrication and Performance Analysis of a Parabolic Trough Solar Collector Water Heater *International Journal of Innovative Research in Science, Engineering and Technology*, 2015, 4(7): 6038- 6043. DOI: 10.15680/IJIRSET.2015.0407122

Eltahir A. M. and Mohamed A. S., Design and testing of a solar Parabolic Trough System for Electricity Generation in Sudan; *Proceeding*, 2013, 1; 246-251,

Egbo G., Sintali I. S. and Dandakouta H., (2008). Analysis of Rim Angle Effect on the Geometric Dimensions of Solar Parabolic-Trough Collector, *International Journal Applied Sciences*, 2008; 2(3); 11-20.