

Thermal Evaluation of a Parabolic Trough Solar Concentrator Using Three Different Receivers

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Abstract

Energy demand, global warming from the fossil fuels and attempt to reduce greenhouse gas emission have placed the centre of attention on how to utilize an alternative sources of energy such as renewable energy technology. This work presents the design, fabrication, and evaluation of the performance of Parabolic Trough Solar Concentrator (PTSC) as a source of heat energy. The PTSC is built, having the Supporting stand made of mild steel and reflector is made of the segmented mirror having a reflectivity of 0.85, a rim angle of 90° and aperture area of 2.5 m² and with a concentration ratio of 11.7. The receiver pipes are made of three different materials; copper, aluminum, and stainless steel. The effects of shifts in focal lengths on the performance of the PTSC with three different receivers were investigated. The results reveal copper as a receiver tube conducts heat to the heat transfer fluid better than aluminum and stainless steel receivers. The focal length of 30 cm gave the best results compared to other values of 27 and 35 cm with a maximum temperature of 114.4 °C. The experimental results revealed that useful heat gained, overall heat loss coefficient, collector efficiency factor, heat removal factor, collector and thermal efficiency were 147.8 J, 5.04 W/m²K, 0.05, 15.05, 0.032% and 15.5% respectively. The study shows that the Parabolic Trough Solar Concentrator as a source of heat energy gives a promising performance. This concentrator will reduce the dependence on the electric power supply, and it controls pollution emanating from fossil fuel, thereby reducing environmental problems.

Keywords: Parabolic Trough Solar Collector, Segmented Mirror, Efficiency, Receivers.

DOI: 10.7176/JETP/9-5-03

Publication date: June 30th 2019

1 Introduction

The solar thermal collector is an economical application of solar energy, a clean and environmentally friendly renewable resource. Instead of using electricity, oil, or gas as a source of heat, is an attractive alternative, mainly in places where electric power is not available. Parabolic cylindrical trough collector is one of the solar concentrator technologies for the transformation of solar energy into thermal drive. Blackened metal tube receiver is fitted on the focal plane of the cylinder, and the channel is rotated about its axis to monitor the motion of the sun. The metal tube transporting heat transfer fluid receives heat energy and gets heated. The hot heat transfer fluid is used for other applications. The performance of the trough collector is affected by different parameters such as aperture diameter, rim angle, the reflectivity of the reflector, absorber size, and shape. To enhance the performance of the cylindrical trough collector, researchers all over the world made sincere efforts to optimize the parameters affecting the performance of the system.

A tubular cavity receiver with air as heat transfer fluid in a parabolic trough solar concentrator system was analyzed (Bader *et al.*, 2015) and found that the collector efficiency varies between 60 to 65%. Kumaresan *et al.* (2012) investigated the performance of a solar parabolic trough collector with a thermal energy storage system. The instantaneous peak efficiency of 62.5% for the parabolic trough was obtained at 12.00 hours. Xiao *et al.* (2014) utilized a V-cavity absorber in linear parabolic trough solar collector and investigated heat transfer performance theoretically and experimentally. The results were in reasonable conformity with the experimental results. Sokhansefat *et al.*, (2015) examined the impact of Al₂O₃ grain concentration in synthetic oil heat transfer working fluid and rate of heat transfer from the absorber tube to the working fluid in the concentrator. The study revealed the direct dependence of the volumetric concentration of nanoparticles in heat transfer working fluid on the convective heat transfer coefficient. Wu *et al.* (2014) proposed a coupled transient model for parabolic trough receiver. The results of the model reflected the average difference in the performance between indoor and outdoor experiments were within 6%. Coccia *et al.*, (2015) carried out the design, construction, and testing of a prototype of parabolic trough collector for industrial heat processes and the system is capable of working with de-mineralized water for temperature up to 85 °C.

Reddy and Satyanarayana (2008) developed a numerical model to examine the heat transfer characteristics of a solar parabolic trough receiver with porous inserts for different fluxes. Mokheimer *et al.*, (2015) performed the optical and thermal analysis of parabolic trough collector under Dhahran's weather conditions. It was found that the system achieved the maximum and minimum optical efficiency of 73.5% and 61%. Huang *et al.* (2012) did a performance simulation of a parabolic trough solar collector and built a new and quick investigative approach

to determine the optical efficiency of the proposed system.

Ladgaonkar and Patil, (2014) performed a selective absorber coating of absorber tube for parabolic trough collector to investigate the performance of the system. The parabolic trough collector overall efficiency, without glass cover per period of two days and with glass cover per period of six days was 48.79% and 55.78%. Wirz *et al.* (2014) built a detailed 3D heat transfer model of parabolic trough concentrators, and the properties of selective coatings and different designs of secondary concentrators were evaluated. Monte Carlo ray-tracing and computational fluid dynamics have been used to find the performance of parabolic trough receiver by Mwesigye *et al.*, (2014) and revealed that the higher concentration ratio increases higher entropy generation. Exergy analysis was carried out to study the effects of operational and environmental parameters on the performance of Parabolic Trough Collectors (Padilla *et al.*, 2015) and found that the highest exergy destruction is due to heat transfer between the sun and the absorber.

Energy demand, global warming from the fossil fuels and attempt to reduce greenhouse gas emission have placed the centre of attention on how to utilize alternative sources of energy such as renewable energy technology (Kotorkoshi *et al.* 2015). It was observed that experimental analysis had not been carried out to assess the effect of the shift in the focal plane with different receiver's materials on the performance of Parabolic Trough Solar Concentrator in Ogbomoso climatic conditions. In this study, the design, construction, and evaluation of a parabolic trough solar collector are presented to examine the effect of the shift in the focal plane with different receiver materials in Ogbomoso environ.

2 Design

2.1 Design Parameters of Parabolic Trough Solar Concentrator, PTSC

The length of the parabolic trough, (standard length available in the market was selected) $L = 2.02$ m. The diameter of the adsorber pipe, $D_i = 0.0325$ m, the geometric concentration level, $C_g = 11.75$. This C_g gives a high temperature at the efficiency of about 60% is as in equation (1), and the radius of the adsorber pipe is 0.0163 m,

The radius of Adsorber, $r_a = \frac{D_i}{2} = \frac{0.0325}{2} = 0.0163$ m

$$C_g = \frac{A_a}{A_r} = \frac{\text{Aperture area}}{\text{Adsorber area}} = \frac{L \times w}{2\pi r_a L} \quad (1)$$

Where $r_a = 0.0163$ m, $C_g = 11.75$, $L = 2.02$ m

$$11.75 = \frac{2.02 \times w}{2\pi \times 0.0163 \times 2.02}$$

Aperture width, $w = 11.75 \times 2\pi \times 0.0163 = 1.204$ m ≈ 1.20 m

the adsorber pipe is placed at focal length (f) is as in equation (2) to minimize heat losses, then,

$$f = h = \frac{d}{4} \text{ or } \frac{w}{4} \quad (2)$$

$$\text{Using } d = 1.20 \text{ m, } f = h = \frac{1.20}{4} = 0.30 \text{ m}$$

Therefore $h = 0.30$ m, where f is the focal length and h is the collector depth, If the focal length is taken as $f = 30$ cm, the equation of the parabola is as in equation (3), $y^2 = 4fx$. (3)

The curve length s' of the parabola curve is obtained as in equation (4)

$$s' = \left[\frac{d}{2} \left(\sqrt{\left(\frac{4h}{d}\right)^2} + 1 \right) \right] + 2f \ln \left[\frac{4h}{d} + \left(\sqrt{\left(\frac{4h}{d}\right)^2} + 1 \right) \right] \quad (4)$$

(Fauziah *et al.*, 2012) Using $f = 0.30$ m, $d = 1.20$ m, $h = 0.30$ m.

$$s' = 2.260 \text{ m}$$

The rim angle can be calculated using equation (5),

$$\cos \phi_R = \frac{2f}{\sqrt{(0.5w)^2 + (d-f)^2}} - 1 \quad (5)$$

where $w = 1.20$ m, $d = 0.30$ m, $f = 0.30$ m

Therefore the rim angle $\phi_R = 90^\circ$

The transmittance of the adsorber product for beam radiation is as given by equation (6). (Fauziah *et al.*, 2012, Kumar, 2013)

$$(\tau\alpha)_b = \frac{\tau\alpha}{1 - (1 - \alpha)\rho_d} \quad (6)$$

Where τ is Transmittance of the receiver's absorber (copper) = 0.88, α is Absorbance of the receiver's absorber (copper) = 0.95, ρ_d is Reflectance of the cover for diffuse radiation (Glass mirror) = 0.94, $(\tau\alpha)_b$ is Transmittance of adsorber product for the beam radiation, hence

$$(\tau\alpha)_b = \frac{0.88 \times 0.95}{1 - (1 - 0.95) \times 0.94} = \frac{0.836}{0.953} = 0.8772$$

2.2 Specifications of Cylindrical Trough Collector

Descriptions	Specifications
Rim Angle(ϕ_r)	90°
Focal Length(f)	0.30 m
Aperture width(W_a)	1.20 m
The outer diameter of the copper tube (D_o)	0.018m
The inner diameter of the copper tube (D_i)	0.018m
Length of the cylindrical trough(L)	2.1 meter
Effective Aperture Area(A_a)	2.42 m ²
Concentration Ratio(C)	11.7
Reflectivity of the collector(ρ)	0.9
Absorptivity of the copper tube(α)	0.8
Transitivity of the copper tube(τ)	0.8
Intercept factor (γ)	0.92

3.0 Fabrication of Parabolic trough collector, PTC

The PTC was constructed using a simple approach. The parabolic trough has components of a receiver and a support structure. The detailed description of each part is as described in this section:

1. Parabolic Trough: Plywood of dimensions 202 cm x 135 cm was used to form the parabolic shape. The plywood was used to provide the mechanical strength to the parabolic trough. A maco was then gummed on the plywood over which segmented mirrors which are 27 in number with dimensions (202 cm x 5 cm) were pasted over it. The segmented mirrors were gummed in such a way that it forms a curve of the parabola. The segmented mirrors were used because they have very high reflectivity of 96%. The reflector made up of segmented mirrors gummed on plywood.

2. Adsorber tube: The adsorber tube is made of copper placed at the focal point of the parabolic trough. The copper tube has a length of 2.21 m with an internal and external diameter of 0.0325 m and 0.0343 m, respectively. Copper, Aluminum, and Stainless steel adsorber tube were used and painted black to absorb the solar radiation reflected by the reflector more efficiently.

3. Support Structure: The supporting frame was designed so that the majority of the weight was placed on the main support structure. The frame was made to be removed for disassembly and transportation purposes. The entire unit was mounted on a single frame for accessible transport site to site. Wheels were attached to the frame to allow easy short-range transportation such as in and out of the laboratory for testing. A jockey wheel was also mounted to assist with the short-range transport of the device and positioning for testing. A threaded strut was developed to hold the mirror at any desired angle. It was necessary for the correct alignment to the sun in any location.

4.0 Experimental Method

Experiments were conducted using the developed parabolic trough collector system as source heat to heat receivers. Copper, Aluminum and Stainless steel receivers were used with three different focal planes of 27, 30 and 35 cm of the collector. The system was mounted in North-South direction in the Department of Mechanical Engineering, LAUTECH, OGBOMOSO. (Lat. 8.1227° N, Long. 4.2436° E, Elevation of 347 m). 12-channel temperature recorder with thermocouples was used to measure the ambient, reflector, adsorber outer and internal temperatures of the system. Solar radiation meter was used to record the intensity of radiation, and wind speed was measured using an environmental meter. Measurements were taken with an interval of 2 minutes between 9 am and 4 pm. The data for one of the typical days were taken for the evaluation of the performance of the PTSC system. Simultaneously, the variations of ambient, reflector, outer, and inner temperature were recorded using the temperature recorder placed at the different points of the trough. The data were recorded to evaluate the performance of the designed system. The photograph of the experimental set up of the system is shown in Figure 1.0.

Performance of Parabolic Trough Collector

The performance analysis characterizes the solar field under different operating conditions for the system under study. The performance parameters used are the solar field efficiency and the useful heat output from the solar field.

Optical Efficiency

The optical efficiency, (η_o) is the amount of radiation absorbed by the absorber tube divided by the amount of direct typical radiation incident on the aperture area. The optical efficiency is normal to the aperture ($\theta = 0^\circ$) is given in equation (7)

$$\eta_o = \rho(\tau\alpha)\gamma \quad (7)$$

Thermal Efficiency

The overall collector efficiency (η_c) is the ratio of the useful output Q_u [W] delivered by the collector to the global irradiance I [W/m²] incident on the collector aperture area A_a [m²] is as given in equation (8)

$$\eta_c = \frac{Q_u}{A_a * I_b} \quad (8)$$

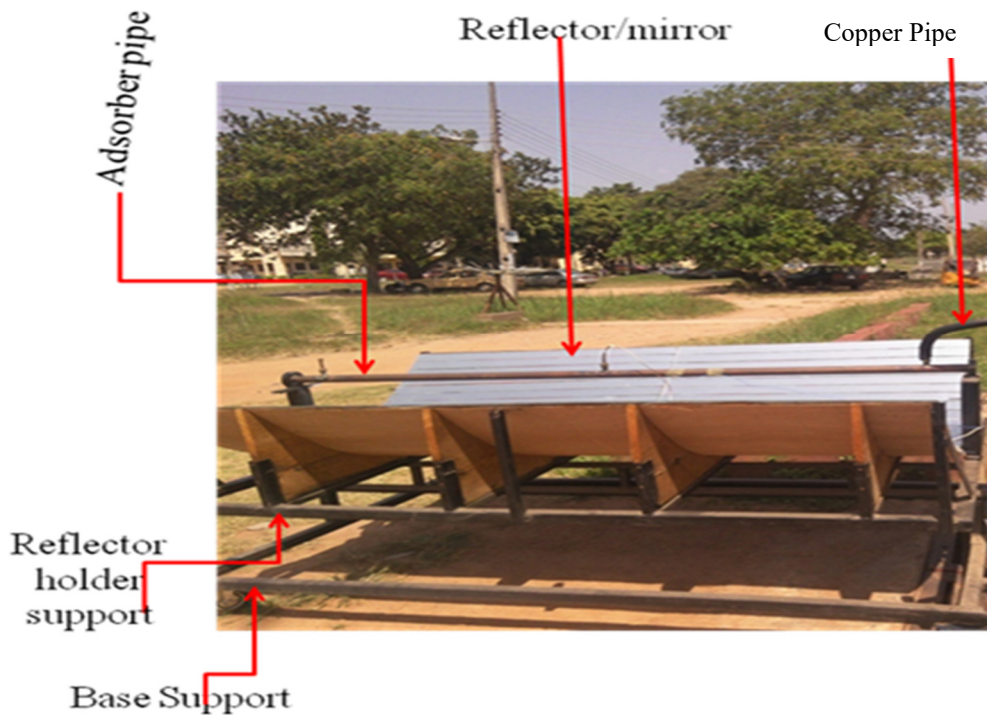


Figure 1.0: Photograph of the developed solar adsorption refrigeration system powered by parabolic trough solar concentrator

The useful output, Q_u of a concentrating collector, is expressed in equation (9)

$$Q_u = m.C_p.(T_o - T_i) = A_a.I_b.\eta_o - A_{abs}.U_l.(T_{abs} - T_a) \quad (9)$$

5. Results and Discussions

Several observations were taken on the PTSC system in the Campus of Ladoke Akintola University of Technology, Ogbomoso. Data are plotted for different days as presented in Figures 2.0 to 15.0

The plot of ambient, reflector, adsorber outer and internal temperatures against the solar time using copper adsorber at a focal length of 30 cm is presented in Figure 2.0. The internal adsorber temperature increased from 31 °C at 9.00 hour to 114.1 °C around noon. It is evident that as the local time increases the internal temperature of the adsorber increases until the peak temperature of 114.1 °C is attained, after which it began to reduce. The temperatures of the reflector and outer surface of the adsorber kept the same sequence.

The graph of ambient, reflector, adsorber outer and internal temperatures against the solar time using aluminum adsorber at a focal length of 30 cm is presented in Figure 3. The internal adsorber temperature was increased from 27 °C at 9.00 h to 77 °C around noon. It is shown that the internal temperature of the adsorber increases as the solar time increases from 9:00 am to 12:47 pm until when the peak internal adsorber temperature of 77 °C is attained, after which it commenced decreasing. The temperatures of the reflector and the outer surface of the adsorber keep to the same pattern.

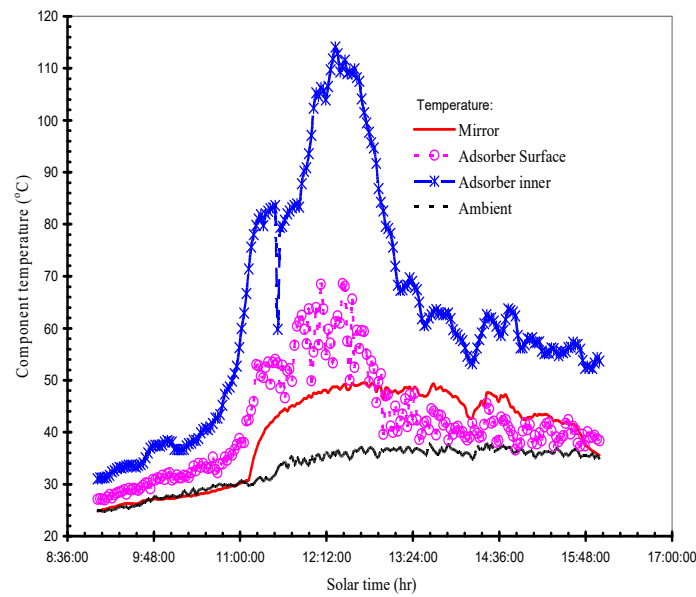


Figure 2: Graph of the ambient, adsorber outer and inner temperatures against the solar time, a copper receiver at a focal length of 30 cm

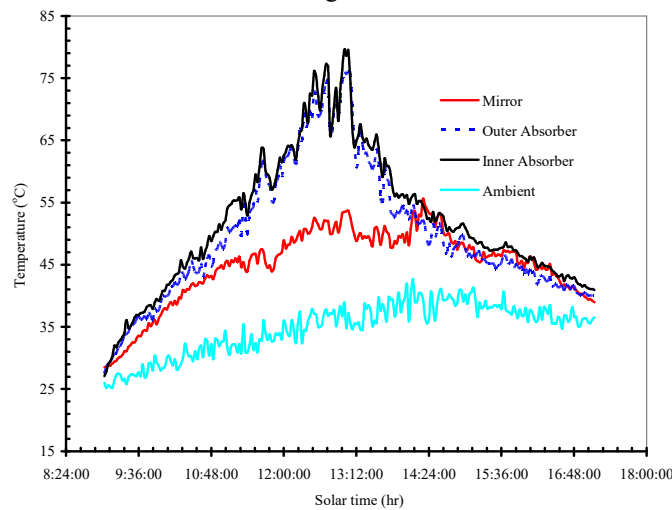


Figure 3: Graph of the ambient, adsorber outer and inner temperatures against the solar time, an Aluminum receiver at a focal length of 30 cm

Variation of the ambient, reflector, adsorber outer and internal temperatures with the solar time using aluminum adsorber at a focal length of 30 cm is as presented in Figure 4. The adsorber outside temperature was increased from 28 °C at 8.24 h to 82 °C around 1 pm. It revealed that the outside temperature of the stainless adsorber increased with the solar time from 8:24 am to 1:10 pm when the peak outside adsorber temperature of 82 °C was reached, after which it began to decrease. The reflector and the inner surface temperature of the adsorber followed the same pattern.

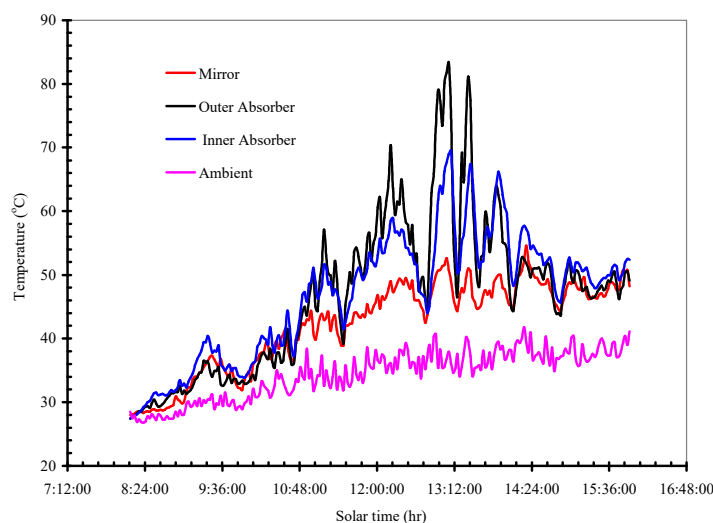


Figure 4: Graph of the ambient, adsorber outer and inner temperatures against the solar time, Stainless steel receiver, the focal length of 30 cm

The graph of the inner adsorber temperature versus the solar time with the different focal lengths of 27, 30, and 35 cm using stainless pipe is as presented in Figure 5. The Figures show that the internal temperature of the adsorber has a peak temperature of 77.8 °C between 1:00 pm and 2:00 pm with the focal length of 30 cm

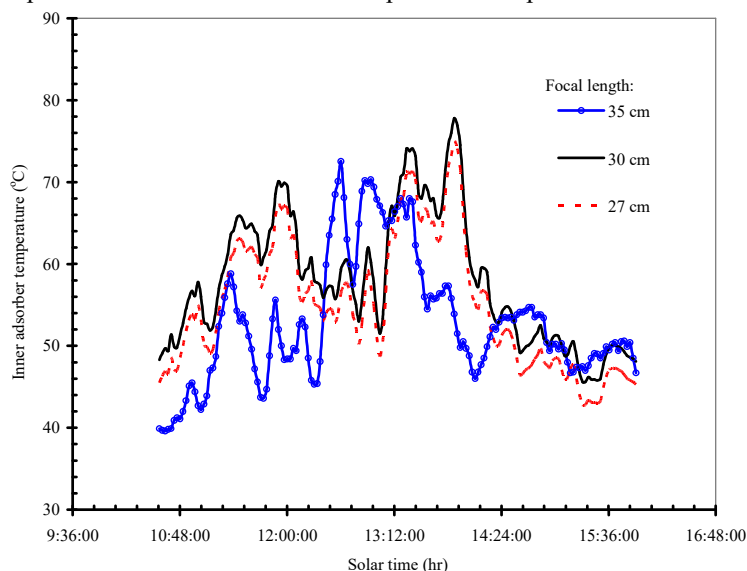


Figure 5: Variation of the inner adsorber temperature with the solar time for the stainless steel receiver at focal lengths of 27, 30 and 35 cm

The variation of the inner and outer adsorber temperature with the solar time at variable focal lengths of 27, 30, and 35 cm for aluminum adsorber is presented in Figures 6 and 7. It compares the effect of the focal length on the aluminum adsorber temperature. As solar time increased, the temperature of the adsorber increased from 8:14 am to 1.00 pm when the peak values of the temperature were obtained. The peak temperature of the inner adsorber was 87.7 °C at 1:00 pm and outer adsorber of 78.7 °C at the focal length of 30 cm. The peak temperature of the inner was 79.5 °C, and the outer gave 76.3 °C at the focal length of 35 cm. The internal temperature of the adsorber was 71.3 °C, and the outer was 68.1 °C at a focal length of 27 cm. The temperatures of the adsorber and the solar intensity began to decrease after 1:00 pm with the increase in solar time. It is evident that for the three different focal lengths, 30 cm gives the highest value of the temperatures because it is one-fourth of the aperture width, 120 cm of the collector designed. The result supports the postulation of Balbir and Fauziah (2003) that the collector would be more efficient at a focal length of 1/4th of the aperture width.

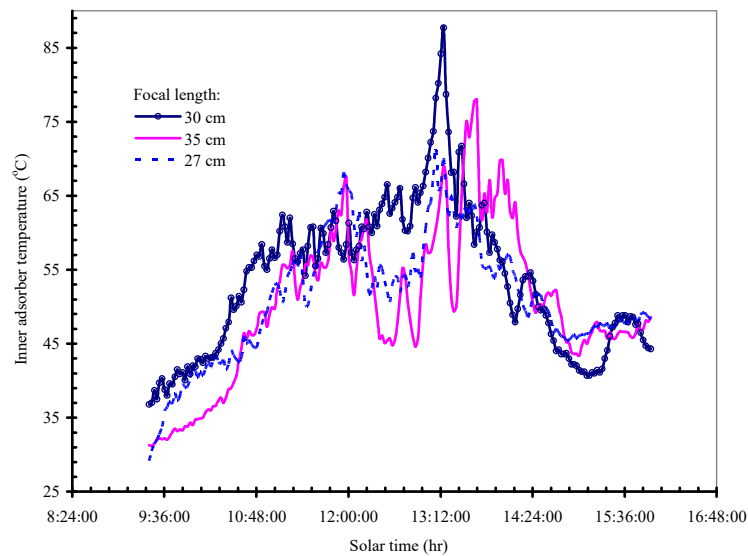


Figure 6: Variation of the inner adsorber temperature with the solar time at a different focal length of 27, 30 and 35 cm (aluminum receiver)

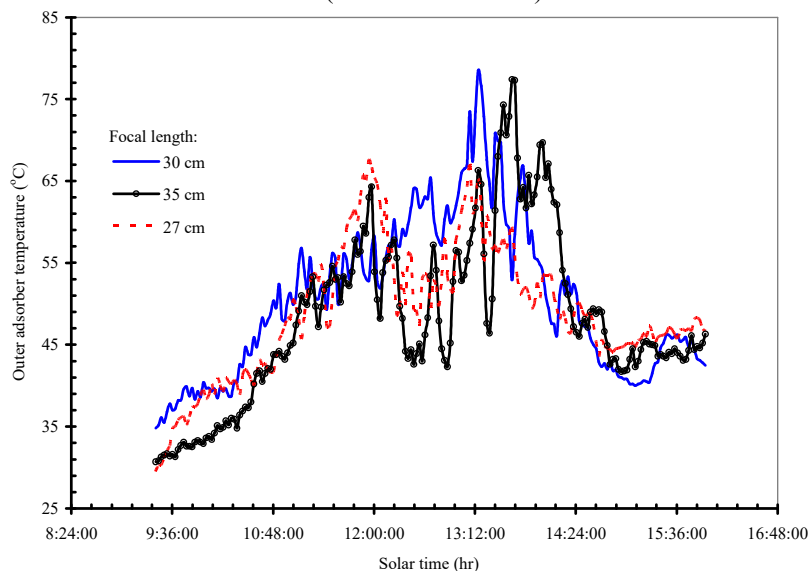


Figure 7: Variation of the outer adsorber temperature with the solar time at a different focal length of 27, 30 and 35 cm (aluminum receiver)

The plot of the instantaneous, thermal and collector efficiencies of the solar parabolic trough collector against local solar time at the focal lengths of 30 cm and 35 cm are presented in Figures 8, 9 and 10. It can be seen that as the local time increased, the efficiencies fluctuated with the solar intensity from 9:00 am to 4:00 pm. The focal length of 30 cm, which is equal to $1/4^{\text{th}}$ of the aperture width of 120 cm, gave higher values of efficiencies when compared with the focal length of 35 cm. The fluctuation and dynamic nature of the efficiencies may be due to the dynamic nature of solar radiation, which is controlled by the weather conditions of different region and localities.

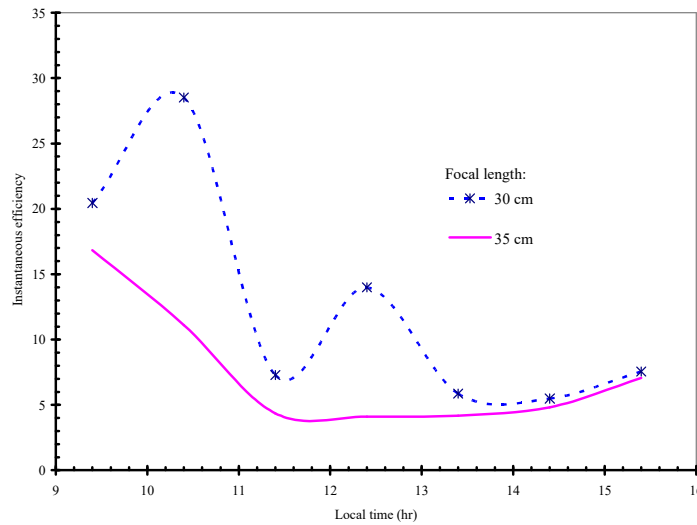


Figure 8: Plot of instantaneous efficiency against local time at a focal length of 30 cm and 35 cm

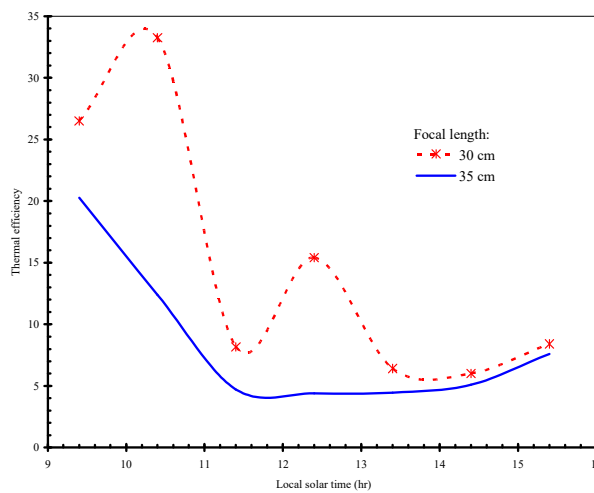


Figure 9: Plot of thermal efficiency against local time at a focal length of 30 cm and 35 cm:

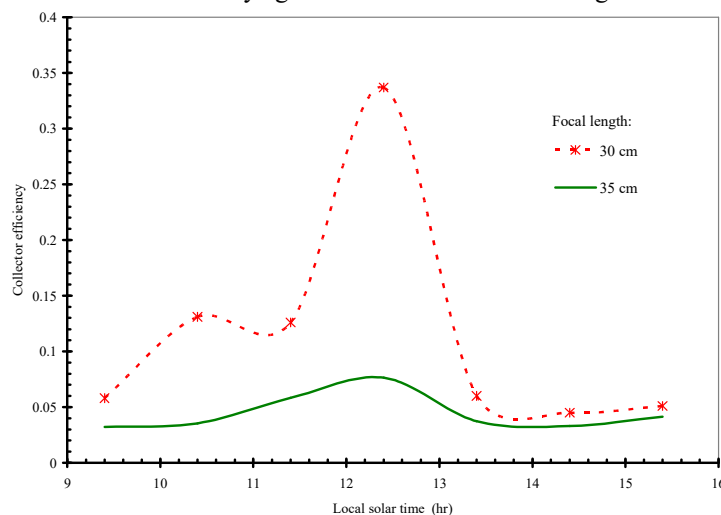


Figure 10: Plot of collector efficiency against local time at a focal length of 30 cm and 35 cm

The comparison of the performance of PTSC with the three receivers' materials of copper, stainless and aluminum adsorber tubes at a focal length of 30 cm. The relationships between the internal temperature of the copper, stainless, and aluminum adsorber tubes are shown in Figure 11. The result shows the relationship between the internal temperature of the copper, stainless, and aluminum adsorber tubes at a focal length of 30 cm. Copper has a peak internal adsorber temperature of 114.4 °C at 12:30 pm

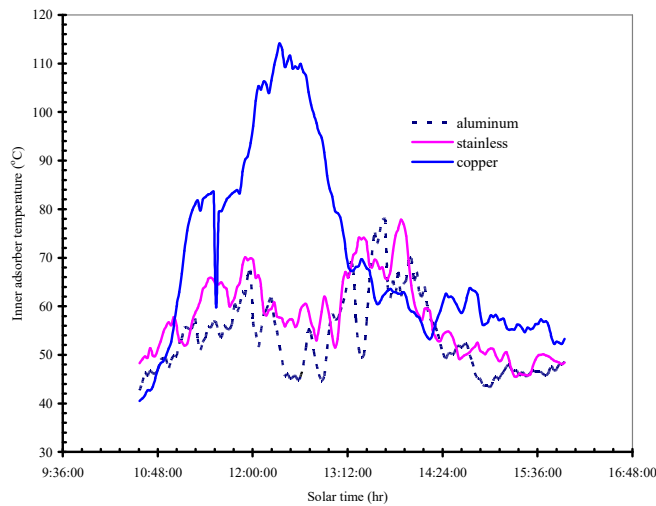


Figure 11: Plot of the inner adsorber temperature (copper, stainless and aluminum steel) against the solar time at the focal length of 30 cm

The nature of solar radiation intensity and wind speed of the test rig climatic condition is presented in Figures 12 and 13. The solar radiation intensity improves with the local time, with a substantial change between 122.9 W/m² to 817.1 W/m² as presented in Figures 12. There is a sharp fluctuation between the time of 11:47 am to 3:59 pm. The solar radiation intensity is attaining its maximum value of 836.8 W/m² at 1:37 pm. The fluctuation of the intensity from 9:00 am to 4:00 pm, has substantial impacts on the temperatures achieved for the day. It determines the dynamic nature of the results obtained in this work. The effect of local time on wind speed is presented in Figure 13. The result shows that the wind speed fluctuates with the local time, and it reveals the dynamic nature of the weather conditions.

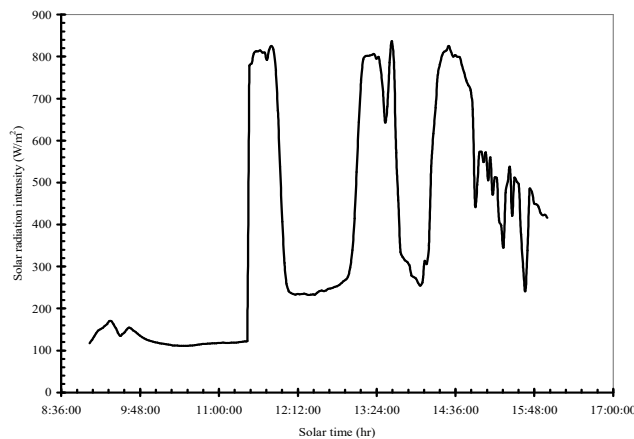


Figure 12: Plot of solar radiation intensity against solar time

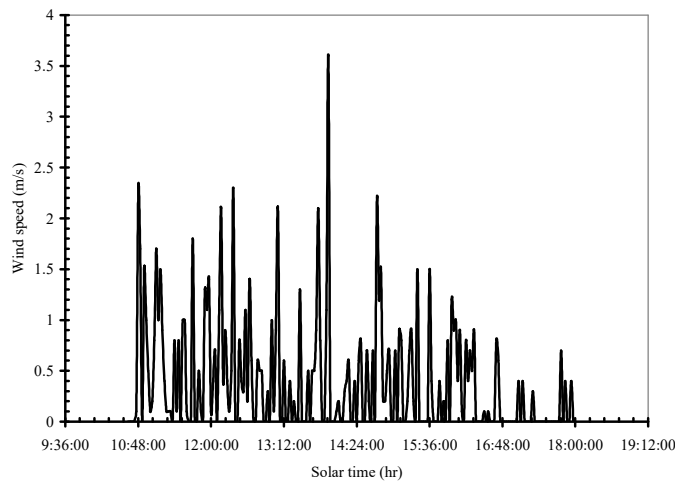


Figure 13: Plot of wind speed against solar time

5 Conclusions

The following conclusions were drawn from the experiment carried out on the designed parabolic trough solar concentrator; A prototype of a Parabolic Trough Solar Concentrator was developed having an aperture width of 1.2 m, collector length of 2.1 m, rim angle of 90° and focal length of 30 cm.

The experimental results reveal that copper as a receiver tube conducts heat to the fluid better than aluminum, and stainless steel receiver, aluminum as an adsorber tube conducts heat to the fluid better than stainless steel adsorber. This work confirms that copper has highest ability to conduct the heat of 401 W/mK, aluminum has higher ability to conduct the heat of 205 W/mK, and stainless steel can conduct the heat of 16 W/mK, thermal conductivity. The focal length of 30 cm, which is equal to 1/4th of the aperture width of 120 cm, gave the best results compared to other values of 27 and 35 cm with a maximum temperature of 114.4 °C around noon.

The performance of the system is found to be satisfactory in the local climatic conditions, and the useful heat gained, overall heat loss coefficient, collector efficiency factor, heat removal factor, collector and thermal efficiency were 147.8 J, 5.04 W/m²K, 0.05, 15.05, 0.032% and 15.5% respectively. The study has shown that the Parabolic Trough Solar Concentrator system will give a promising performance as a source of heat energy in southwestern climatic conditions of Nigeria. By manufacturing such type of solar concentrator adds a new dimension to the world of energy. This concentrator gives some amount of relief to the energy world by reducing the dependence on the electric power supply, and it controls pollution emanating from fossil fuel, thereby reducing environmental problems.

Nomenclature

PTSC - Parabolic trough solar concentrator

Q_u - Useful heat output

C_p - Specific heat capacity

T_i - Inner Temperature

I_b - Incident Solar Radiation

T_a - Ambient temperature

η - Thermal efficiency

m - Mass Flow Rate

T_o - Outlet Temperature

A_a - Aperture Area

τ - Transmittance of the receiver

α - The absorbance of the receiver

ρ_d - The reflectance of the cover for diffuse radiation

$(\tau\alpha)_b$ - The transmittance of adsorber product for the beam radiation

Acknowledgments: The financial assistance through Research Grant from the Institute of Food Security, Environmental Resources and Agricultural Research (IFSERAR), Federal University of Agriculture, Abeokuta (FUNAAB) is highly appreciated. The Research Grant number is UNAAB/IFSERAR/IRG 53.

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