Experimental Analysis of the Parabolic Trough Solar Concentrator Water Heater

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Abstract

Solar energy is one of the most promising sources of alternative energy and solar water heater is a medium of making the best use of this renewable energy for human benefit. This work aimed at examining the performance of Parabolic Trough Solar, PTS water heater with black, grey, and uncoated receiver tubes made of galvanized iron. A prototype set-up of PTS Concentrator was evaluated with 10-liters of water, having an aperture area of 2.46 m^2, and a segmented mirror to form the parabola.

The results reveal that the black receiver tube conducts heat to the heat transfer fluid better than other receivers. The maximum water temperature obtained from the black-coated receiver was 70^oC with a thermal efficiency of 8.1%. The study shows that the solar concentrator as source of heat energy gives the best performance with the black receiver and controls pollution emanating from fossil fuels, thereby reducing environmental problems.

Keywords: Parabolic trough, receiver, absorber, solar water heater

1. INTRODUCTION

Solar energy is an essential source of energy for our world. The average solar energy reaching the earth in the tropical region is approximately 1 kWh/m^2 and total radiation over a day is nearly 7 kWh/m^2. The solar constant is the rate at which energy is obtained from the sun on a unit area perpendicular to the rays of the sun, at the average distance of the globe from the sun is 1353 W/m^2. The energy from the sun is utilized for different applications principally as generation of power known as manufacturing process heat applications and generation of solar electricity (Sukhatme, 2007).

The expenditure of energy in the domestic area is important as it accounts for nearly one-third of the entire delivered-energy utilize and carbon dioxide discharges of this delivered-energy expend, nearly a quarter is for water heating. Water heating is offered by burning non-industrial fuels, this causes a reduction of plantations and hence its effects climate change and commercial fuels such as liquefied petroleum gas (LPG), kerosene oil, coal; through the use of electricity in urban areas or direct combustion (Sambo, 2005). Solar energy is one form of alternative energy that is accessible at no cost and the simplest way of utilizing it is by promptly converting it into valuable thermal energy. A classic appliance that does the transformation is a solar water heater (SWH). It heats the heat transfer fluid such as water, air for domestic usage, or non-freezing liquid. Hence Sun as a source of energy that is both free and renewable has reduced heating expenses by a huge amount (Dikshita, et al.(2020),

Sagade (2013) carried out an experiment on a parabolic trough built of fiberglass-reinforced plastic with its aperture area coated by aluminum foil. A low-cost FRP parabolic trough system confirmed to be valuable for mechanized heating applications as well as domestic heating in Indian weather conditions. Valan and Sornakumar (2007) described the design and production of a smooth 90°-rim angle fiberglass-reinforced parabolic trough for heating water purposes. The results depict a high accuracy of the parabolic surface.

Ruby *et al*. (2012) carried out a performance analysis of a high-temperature solar thermal system and steam was changed into hot water for cleaning and sterilization processes. Qu et al. (2006) developed a linear tracking parabolic trough reflector focused on a surface-treated metallic pipe receiver enclosed in an evacuated transparent tube. The experiment revealed that hot water at 165°C flown through a 6 m by 2.3m Parabolic Trough Solar Collector with solar insulation of 900 W/m^2 and the collector efficiency is 55%. Brooks *et al*.(2006) carried out performance studies of parabolic trough solar collectors using water as the working fluid. The experiment was carried with an evacuated glass shielded receiver and an unshielded receiver. The maximum thermal efficiencies were determined for the shielded receiver and an unshielded receiver as 53.8% and 55.2% respectively.

Singh and Sulaimon (2003) performed an experiment on solar parabolic trough collectors at equilibrium between the thermal losses and aperture area. It was found that as the concentration ratio increases, heat removal factor and efficiency reduce. Singh *et al.* (2012) manufactured a solar parabolic trough water heater for hot water generation using two different receiver tubes. The efficiencies obtained for copper tube receiver and aluminum tube receiver were 20.25% and 18.23% respectively. Bharti et al (2018) performed an experimental examination of a small-sized solar parabolic trough collector (PTC) system with an aperture area of 4.075 m^2 to investigate the PTC performance. It was revealed that the copper receiver tube has better performance with a peak thermal efficiency of 35.9% and the peak thermal efficiency of 61.4% was obtained when the receiver was covered with an acrylic tube. Sangotayo *et al*. (2019) presented the evaluation of the performance of Parabolic Trough Solar Concentrator (PTSC) with three-receiver pipes are made of copper, aluminum, and stainless steel. The results reveal copper receiver tube conducts heat to the heat transfer fluid better than aluminum and stainless steel receivers.

In the present work, a new parabolic trough collector system with a manual tracking system has been developed for hot water generation, Fabrication and design of a solar parabolic trough is done using locally available materials with black, grey, and uncoated receiver tubes made of galvanized iron. The great advantage of the solar trough is that it is clean, cheaper, and can be supplied with thermal energy without any environmental pollution. A prototype set-up of Parabolic Trough Solar Concentrator was evaluated with 10 liters of water, having an aperture width of 1.2 m, collector length of 2.1 m, rim angle of $90^{o,}$ and focal length of 30 cm using a segmented mirror sheet in the shape of a parabolic cylinder to reflect and concentrate Sun on the focal line during March and April 2021 at Ogbomoso (8.1227° N latitude, 4.2436° E latitude).

2. SYSTEM DESCRIPTION

The set-up of Parabolic Trough Solar Concentrator, PTSC has the following experimental characteristics; easy constructible, strong and stable structure, lightweight, and low cost. The concentrator has a segmented mirror which is 27 in number with dimension (202 cm × 5 cm) and was pasted on plywood gummed with maco. The segmented mirrors were gummed in such a way that it forms a curve of the parabola. The segmented mirror was used because it has high reflectivity of 96%. The segmented mirror sheets are installed on the parabolic-shaped supporting structure. The size of the segmented mirror is the same as that of the size of the supporting structure. The Rim angle is 90° and the total aperture area is 2.424 m^2.

The parabolic trough solar collector utilizes a segmented mirror in the shape of a parabolic cylinder to reflect and concentrate sun radiations towards the receiver tube placed at the focus line of the parabolic cylinder. The receiver absorbs the incoming radiations and transforms them into thermal energy, then transported and collected by a heat transfer fluid medium circulating within the receiver tube. The receiver tube is made of galvanized iron tubes with black, grey, and uncoated receiver tubes. The experimental setup of the constructed parabolic trough concentrator for domestic hot water application is shown in Figure 1.0. The test rig consists of a solar collector, storage tank of 10 liters capacity, control valve that regulates the flow rate of the water.

The measuring instruments are attached to the test rig to measure and record the data. The following instruments were used; SD Environmental meter was used to measure relative humidity and wind speed, 12 channel SD data logger temperature recorder was used to measure temperatures, and solar power meter was used to measure solar intensity.

Figure 1: The parabolic trough system with storage tank

3.0 CONSTRUCTION OF PARABOLIC TROUGH SOLAR CONCENTRATOR, PTSC

The PTSC 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 mechanical strength to the parabolic trough. The segmented mirrors were gummed in such a way that it forms a curve of the parabola. The reflector is made up of segmented mirrors gummed on plywood.

2. Absorber tube: The absorber tube is made of Galvanized iron (GI) placed at the focal point of the parabolic trough. The Galvanized iron has a length of 2.21m with an internal and external diameter of 0.029 m and 0.031 m, respectively. Coated, uncoated, and grey receiver tubes were used to absorb the solar radiation reflected by the reflector more efficiently.

3. Support Structure: For the collector precision and stability, 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 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. Sun Tracking: Manual sun-tracking was done during the experimentation period. The system was adjusted into the north-south direction, to obtain the maximum available solar radiations. The tracking was done to rotate the collector about the east-west axis. The horizontal axis tracking will be obtained through a manual observation of the reflection of the sun's rays on the reflective surface.

Table 1.0 shows the parameters and dimensions of the terms used in the experimentation.

Table 1.0 Dimension of the Collector

Item	**Symbol**	**Black , Grey Uncoated, , (GI)**
Rim Angle	(ϕr)	90^0
Focal Length	(f)	0.3m
Aperture width	(W_a)	1.20m
The outer diameter of the GI tube	(D_o)	0.031m
The inner diameter of the GI tube	($D_{I)}$	0.029m
Length of the cylindrical trough	(L)	2.1m
Effective Aperture Area	(A_a)	2.42m
Concentration Ratio	(C)	11.7
Reflectivity of the collector	(ρ)	0.63
Absorptivity of the GI tube	(α)	0.45
Transitivity of the GI tube	(ꞇ)	0.8
Intercept factor	(ϒ)	0.92

3.6 **Experimental Setup and** Procedure

Experiments were conducted using the developed parabolic trough collector system as source heat to heat receivers. Galvanize iron receiver was used with three different receivers black coated, gray coated, and uncoated. The experimental setup comprises a parabolic trough collector tested with three different receivers made of galvanizing pipe, a storage tank of 10 liters capacity, receiver's pipe of length 2.1m, reflector material is a segmented mirror carefully gummed to maco placed on the plywood to form the parabola shape. The water supply tank is located above the receiver's pipe level to permit the heating fluid to flow spontaneously without the pumping system. The storage tank is filled with water.

The experiment procedure began by flushing the system. Then, the system was filled with water and the good working status of all measuring instruments was examined, Coldwater from the storage tank enters the receiver of the parabolic trough collector. The tank was positioned above the level of the collector to ensure the natural flow of water. As the water in the receiver tube, which is positioned at the focal axis of the trough, is heated by solar energy, heated water flows spontaneously to the top of the water tank and is substituted by cold water from the bottom of the tank. When the water becomes heated upon rising to the collector, its density will reduce and the lighter-density water will move up and be stored on top of the storage tank. Higher-density water from the bottom of the tank again enters the parabolic trough and gets heated and moves up and stored in the top of the storage tank.

The water inlet and outlet temperatures of the receiver tube, the ambient and the reflector temperatures, the surface temperature of the receiver, the solar radiation intensity, and relative humidity were continuously measured during the experimental period of 9.00 am to 4.00 pm. A 12-channel temperature recorder with thermocouples was used to measure the ambient, reflector, receiver outlet, and inlet temperatures of the system. A solar radiation meter was used to record the intensity of radiation, and wind speed and relative humidity were measured using an Environmental meter. Measurements were taken with an interval of 5 minutes for the experimental period of 9 am to 4 pm a day. The data for one of the classic days were taken for the performance examination of the PTSC system. Concurrently, the variations of ambient, reflector, outlet, and inlet temperatures were measured using a K-type thermocouple connected to the temperature recorder positioned at the different points of the trough. The data were recorded to compute the performance parameters of the concentrator for three galvanized iron tubes with black, grey, and uncoated receiver tubes, at 0.003 m^3/s mass flow rate of water. During the experimentation, a cylindrical parabolic collector was oriented with its focal axis pointed in the north-south (N-S) orientation in the department of Mechanical Engineering Workshop LAUTECH Ogbomoso.

4. THERMAL PERFORMANCE CALCULATIONS

The useful energy delivered from the concentrator can be given using Eqn. 1 (Bharti *et al.* 2018)

$$Q_u = \dot{m} c_p (T_o - T_{in}) \quad (1)$$

Where, Q_u is the useful energy delivered from the concentrator (W); $\dot{m}$, the mass flow rate of 0.003 kg/s; T_o, outlet fluid temperature (°C); T_{in}, inlet fluid temperature (°C); C_p, specific heat of water (kJ/kg°C);

The useful energy gain per unit of the collector length can be expressed using Eqn 2

$$Q_u^{1} = \frac{\dot{m} c_p (T_o - T_{in})}{L} \quad (2)$$

Where Q_u^{1} is the useful energy gain per unit of the collector length; and L is the length of the concentrator (m). The instantaneous collection efficiency can also be calculated using Eqn. 3

$$\eta_{th} = \frac{m c_p (T_2 - T_1)}{A_a I_b} \quad (3)$$

Where η_{th} is the instantaneous collector efficiency and the heat lost, H_l can also be calculated using Eqn. 4

$$H_l = A_a I_b - \dot{m} C_p (T_2 - T_1) \quad (4)$$

Where, m = mass flow rate of fluid (kg/sec) ,Cp= specific heat capacity of fluid is 4200kJ/kgK for water ,T_2= Maximum temperature attained by fluid (^{0}C) ,T_1= Initial temperature of fluid (^{0}C) ,A_a= Aperture area (m^2) ,I_b= Solar Intensity $\frac{W}{m^2}$

In this study, an evaluation of a parabolic trough solar collector water heater is presented to study the effect of black coated, uncoated, and grey painted receiver galvanized iron pipes on thermal efficiency in Ogbomoso environs. Simultaneously, the variations of ambient, reflector, outlet, and inlet temperature were recorded using the temperature recorder placed at the different points of the trough. The data recorded were used to compute the performances of the concentrator.

5. RESULTS AND DISCUSSIONS

Several observations were taken on the PTSC system in the Campus of the Ladoke Akintola University of Technology, Ogbomoso. Data are plotted for different days as presented in Figures 2 – 6. Figure 2.0 presents the variation of Solar Intensity against time. Figure 2 indicates that the highest amount of solar intensity of 358 W/m^3 is around 12 noon to 1.30 pm for the three different days with different receivers. It shows the dynamic nature of solar radiation with time which is the principal determinant of the performance of the PTSC. It determines the amount of heat received by the heat transfer fluid in the receiver and the ambient temperature.

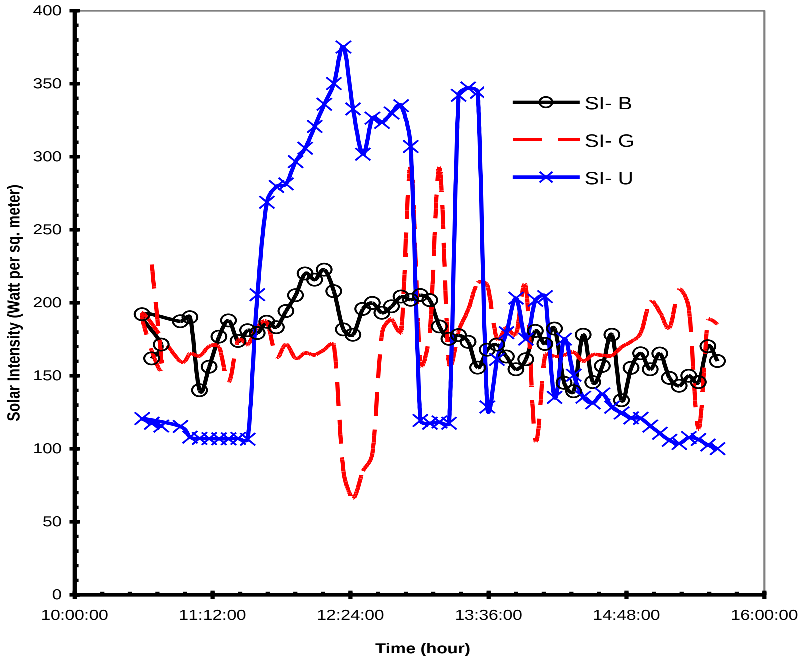

Figure 2.0 Variation of Solar Intensity against time

Figure 3 displays the fluid Inlet temperature of the 3 receiver tubes against time. It indicates that the grey receiver tube received the highest fluid Inlet Temperature and the black-coated receiver tube has the lowest fluid Inlet temperature because of the corresponding change in the amount of solar intensity and ambient temperature.

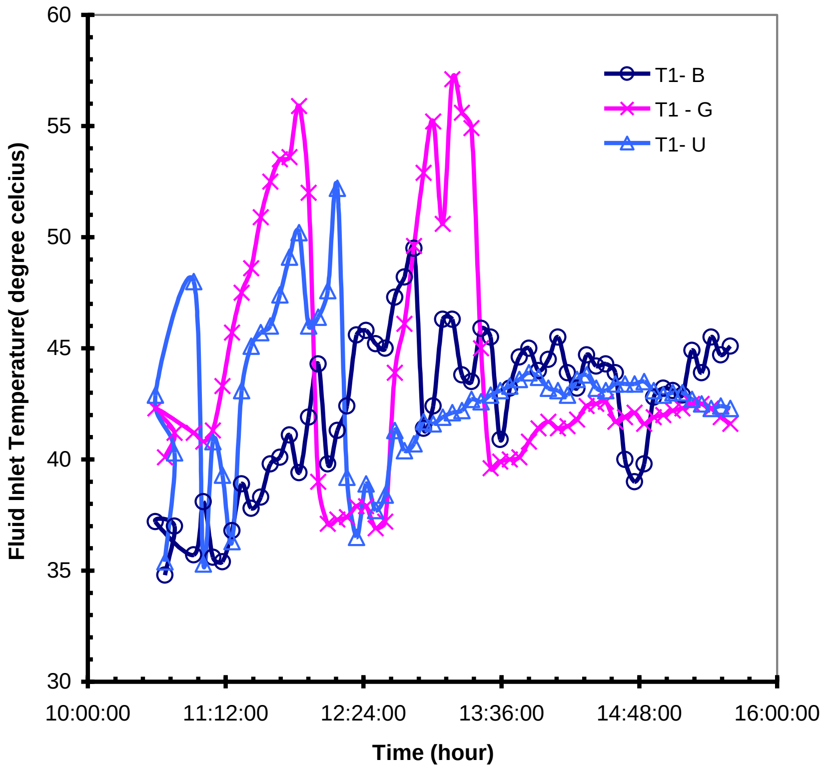

Figure 3.0 Plot of Fluid Inlet Temperature of the receivers against time

Figure 4 displays the receiver temperature of the three receivers against time. It indicates that the black-coated receiver tube has the highest temperature of 58 ^{o}C and the uncoated receiver tube has the lowest temperature of 38 ^{o}C, it shows that the black absorber has the highest absorbing capacity because the black body is a good absorber of heat.

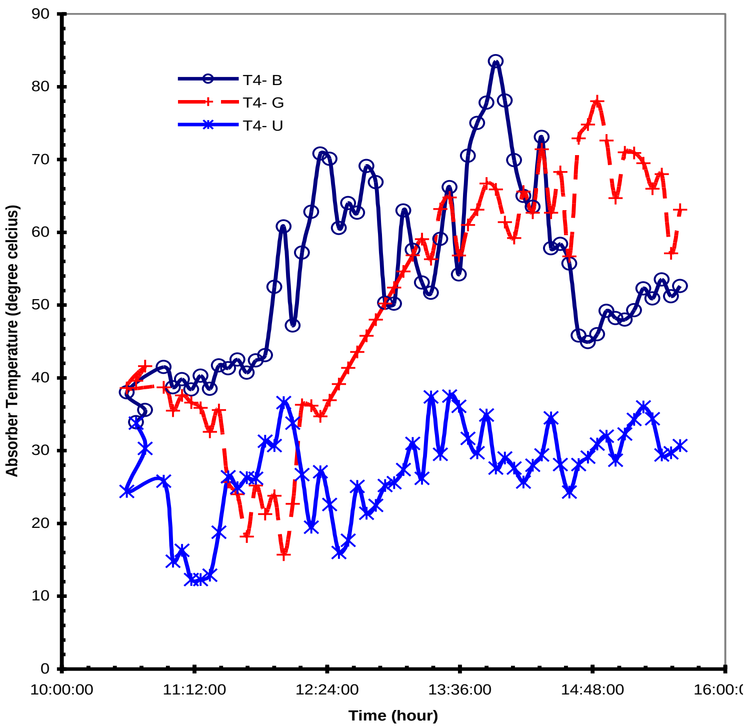

Fig 4 Graph of Absorber temperature of the receivers versus time

Figure 5 presents the fluid outlet temperature of the three receivers against time. It indicates that the black-coated receiver tube has the highest temperature of 70 ^{o}C and the uncoated receiver tube has the lowest temperature of 55 ^{o}C, it shows that the black absorber conducts the highest heat to the fluid, because the black body is a perfect absorber of heat.

Fig 6 presents the heat loss of the 3 receivers against time. It indicates that the uncoated receiver tube losses the highest heat and the black-coated receiver tube losses the lowest heat. it shows that a black absorber is a good absorber of heat. It shows that the black painting of the receiver has enhanced the retaining heat capacity of the receiver hence reduces the heat loss from the receiver.

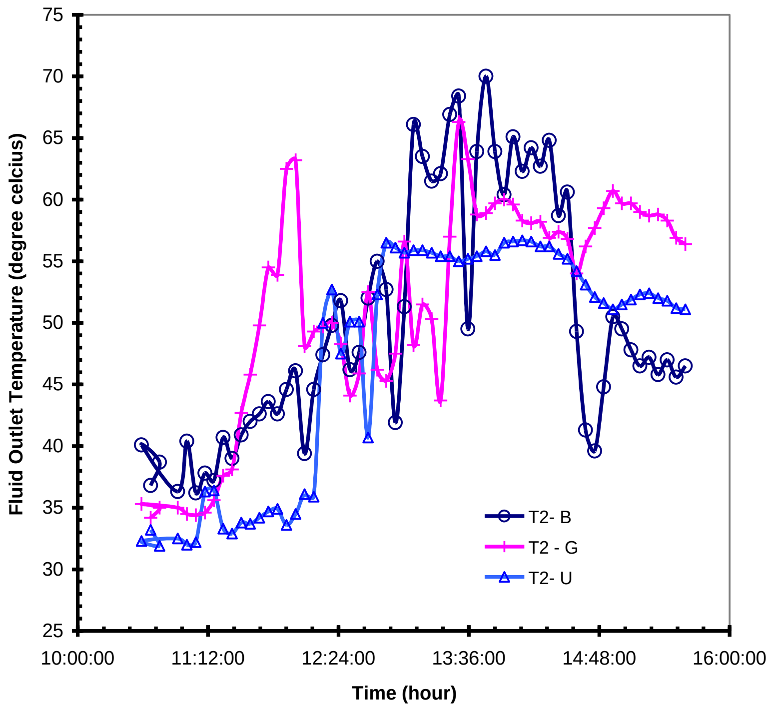

Fig 5 Fluid Outlet Temperature of the receivers against time

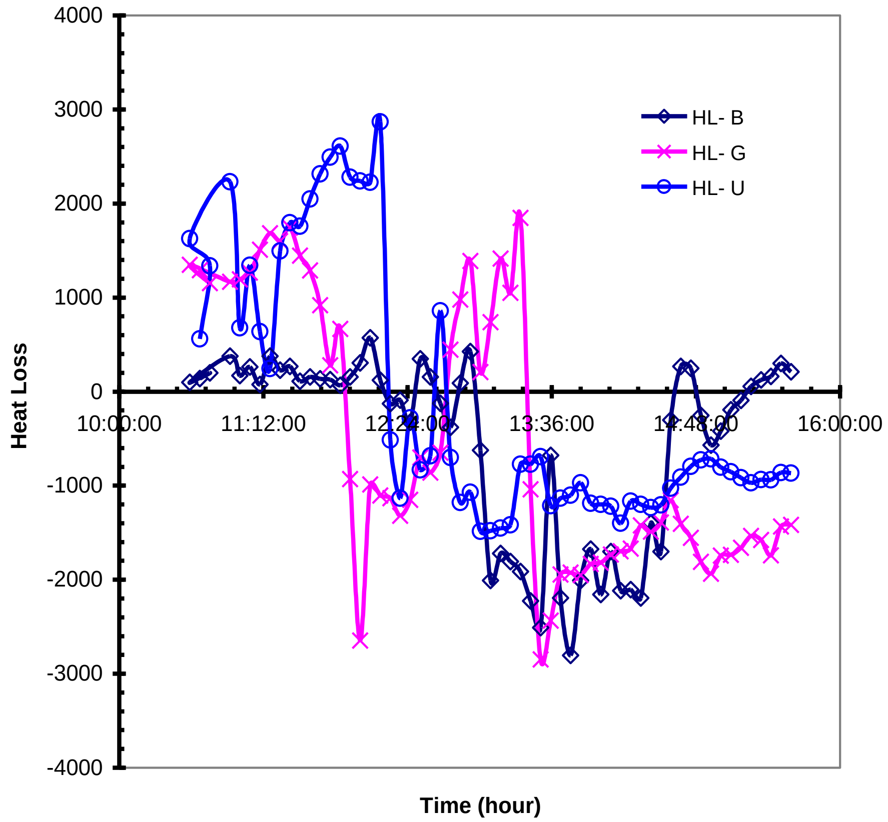

Figure 6 Heat loss of the receiver tube against time

Figure 7 presents the thermal efficiency of the receivers against time. It indicates that the black-coated receiver tube has the highest collector efficiency of 8.1 % with a minimum solar intensity of 280 W/m^2 and the grey-coated receiver tube has an efficiency of 7.8 % with a maximum solar intensity of 358 W/m^2, hence black absorber has the best performance while comparing with the other receivers.

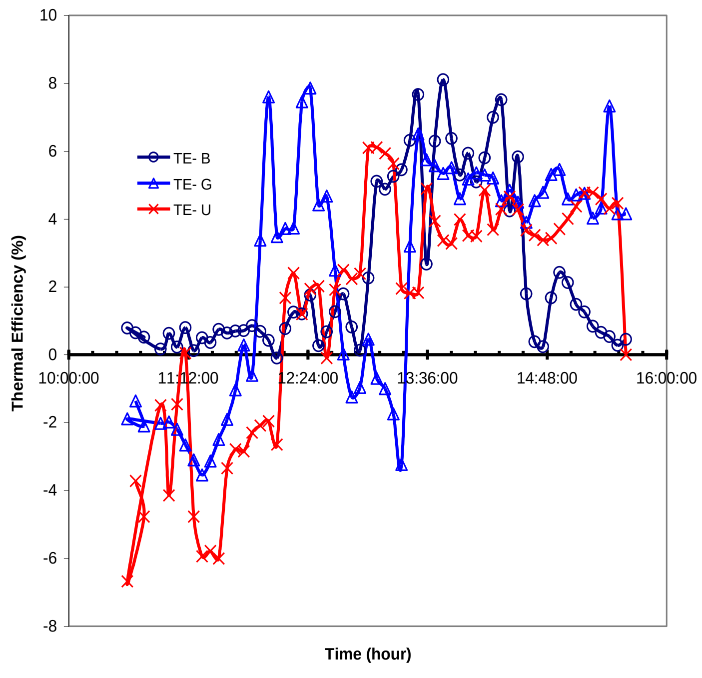

Figure 7 Thermal Efficiency of the receivers against time

6. CONCLUSION

The following conclusions were drawn from the experiment carried out (March and April 2021) at Ogbomoso (8.1227° N latitude, 4.2436° E latitude) on the developed prototype parabolic trough solar concentrator, having an aperture width of 1.2 m, collector length of 2.1 m, rim angle of $90^{o,}$ and focal length of 30 cm. The experimental results reveal that the black-coated receiver tube conducts heat to the heat transfer fluid better than the grey and uncoated receiver tube, the grey absorber tube conducts heat to the fluid better than the uncoated. the maximum water temperature obtained from the black-coated receiver tube was 70^oC proving to be the most effective of the three types of receiver tubes with a thermal efficiency of 8.1% peak value, then the grey coated receiver tube attained a maximum temperature of 66.3^oC with a thermal efficiency of 6.1% peak value and the uncoated receiver tube with a maximum temperature of 56.7^oC with a peak thermal efficiency value of 6.0%. The study has shown that the Parabolic Trough Solar Concentrator system will give a promising performance as a source of heat 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 fuels, thereby reducing environmental problems.

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