THE EFFECT OF TILT ANGLE AND MASS FLOW RATE ON THE PERFORMANCE OF A PARABOLIC TROUGH SOLAR CONCENTRATOR VIA EXPERIMENTATION

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ABSTRACT

Solar energy is widely regarded as a very promising alternative energy source due to its potential to satisfy a substantial portion of global energy demand. The efficacy of a solar concentrator is contingent upon operational and weather factors. This paper presents an experimental evaluation of the effect of tilt angle and mass flow rate on the effectiveness of a parabolic trough solar concentrator

The parabolic trough solar collector was subjected to experimental testing in LAUTECH's Ogbomoso engineering facility. It has a collector length of 2.1m, an aperture width of 1.2m, an adjustable rim angle of 75^o, 90^{o,} and 105^o, a focal length of 30 cm, a 10-liter storage reservoir with varying flow rates of 0.0004 m^3/s, 0.0008m^3/s, and 0.0012m^3/s. The temperatures were measured with a 12-channel temperature recorder (SD data logger), while the solar radiation was measured with a solar meter and water was used as a working fluid. Thermal performance analysis was conducted to ascertain the impact of tilt angle, mass flow rate, and weather conditions on the solar concentrator's effectiveness.

The results indicate that the system has a greater thermal efficacy with weather elements such as solar intensity and ambient temperature at higher mass flow rates and a 90^o tilt angle. This concentrator aids the energy industry by decreasing reliance on electricity and pollution from fossil fuels, thereby minimizing environmental and health issues.

Keywords: Alternative Energy, Concentrator, Effectiveness, Environment, Tilt Angle,
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1. INTRODUCTION

Solar energy is a viable alternative energy source that might meet a large amount of the world's energy needs. Solar energy is available worldwide and pollution-free. This makes solar energy a more viable alternative to traditional energy sources and conversion of solar energy into thermal energy is an efficient harvesting method. Solar collectors are crucial to turning solar energy into thermal energy that can be recovered from the working fluid. Collectors include flat plate collectors (FP), compound parabolic concentrators (CPC), evacuated tube collectors (ETC), and parabolic trough collectors. Parabolic troughs are solar collectors with a parabolic shape due to their straight longitudinal axis and curved transverse axis. A polished metal mirror or high-reflectivity substance is often applied to the trough's inner surface. The focal lines focus on solar energy that aligns with the mirror's plane of symmetry. The focal lines indicate where the absorber tubes hold the heating working fluid and the heat transfer fluid from the absorber raises steam temperature in a typical turbine generator, enabling efficient and cost-effective electricity generation (Jaaz et al. 2017; Sangotayo et al. 2019).

Zou et al. (2016) tested a small-scale parabolic solar collector (PTC) for water heating in cold climes using a parabolic reflective mirror to improve collector reflectivity. The research found that flow rate increased thermal efficiency. However, excessive wind velocity decreased thermal efficiency. Under low fluid temperatures, the PTC system worked as expected, according to the author's analysis. Thus, this method could be used in extremely cold areas. Canavarro et al. (2014) investigated optical setups to improve large-scale parabolic trough systems. The article discussed tubular receivers, specifically the hamlet concentrator, to reduce Fresnel losses by removing glass envelopes. This article uses a gap in trough designs to reduce shadow losses. Rodriguez et al. (2015) used a second-stage flat mirror to increase a parabolic trough's concentration ratio. Using a flat secondary reflector to increase the parabolic trough collector concentration ratio is cost-effective. Zemax software was used to validate experiment equations via ray tracing and the inclusion of a secondary reflector raises the concentration ratio, but shadow projection decreases the absorber's energy intake. Jebasingh et al. (2016) reviewed the solar parabolic trough collector and the study emphasized the performance of solar energy and parabolic trough collectors. It was revealed that optimizing absorber material, coatings, and working fluids improve parabolic trough collector thermal performance.

Kumar et al. (2015) assessed solar parabolic trough collector performance year-round in Bhiwani, India. The serpentine parabolic trough collector's thermo-optical performance was determined for each month's day. The highest water temperature is 11.1°C in April and the lowest in December (2.2°C). July has the highest immediate thermal efficiency (66.78%) and optical efficiency (72.26%). Summer system performance is better than other seasons. Zheng et al. (2016) investigated a new compound parabolic concentrator solar collector numerically and experimentally. The compound parabolic collector lowers heat loss, increases thermal efficiency, and resists freezing. The experiment lasted a day and captured data every 10 minutes. Thermal efficiency increased from 55% to 60.5% during testing. Numerical and experimental data showed an 8.07% maximum deviance. Jaaz et al. (2017) developed compound parabolic concentrating (CPC) photovoltaic solar collectors. A non-imaging Fresnel lens was used to collect massive amounts of sunlight on the parabolic trough and the tracking mechanism improved the performance of the collector, A solar parabolic trough collector working fluid experiment was conducted by Bellvs et al. (2017). A simulator EES (Engineering Equation Solver) was used to compare thermally efficient operating fluids and maximum efficiency (47.48%) was achieved with liquid sodium with pressurized water works best up to 550K.

Ratismith et al. (2017) developed a solar thermal non-tracking concentrator collector. This article compared concentrator trough performance to a non-concentrator collector with similar tube counts under typical conditions. The results demonstrated a potential improvement in output temperature gain, and the collector design promises better versatility for low-tech rural home applications. Manifold header pipes immersed in flowing liquid boost thermal efficiency by 20% by increasing heat transfer. Desai et al. (2014) optimized parabolic trough collector-based concentrating solar thermal power plants. A 1MW plant with 3.5MPa to 7.5MPa turbine inlet pressure enhances plant efficiency by 18%. Increased design radiation boosts power production. The optimal direct normal irradiance (DNI) for a concentrator plant is 600W/m^2 for the lowest levelized cost of electricity. Jina et al. (2016) analyzed parabolic trough solar collector similarities. It was revealed that increased DNI boosts collector efficiency with an inaccuracy of 0.75%, the anticipated outcomes match experimental data from literature and a scaled model can properly study parabolic trough collector effectiveness.

Pandolfini et al. (2014) modeled numerous parabolic reflector flat panel collectors thermodynamically. The receiver tube is covered in glass to decrease energy loss. Ray tracing calculates optical gain, and the multiple parabolic trough collector collects 10% of annual direct beam radiation compared to 5% for a flat plate collector. Sangotayo and Peter (2020) investigated how thermo-physical factors affect parabolic trough solar collector performance. The Parabolic Trough Solar Concentrator's thermal performance was considerably affected by water-based nanofluids. TiO_2, CuO, and Al_2O_3 increase heat transfer coefficient by 20%, 21%, and 14%, respectively, as thermal conductivity increases by 23% and specific heat capacity decreases by 30%. The efficacy of a Parabolic Trough Solar Concentrator (PTSC) was assessed by Sangotayo et al. (2019) through the utilization of receiver pipes made of copper, aluminum, and stainless steel. Copper receiver tubes provide superior heat transfer efficiency in comparison to both aluminum and stainless steel receiver tubes.

Numerous scholars have conducted extensive research on the Parabolic Trough Collector (PTC) for various applications, including distillation, water heating, steam generation, electricity generation, and solar thermal power plants. However, only a limited number of researchers have focused on enhancing the efficiency of the PTC by manipulating the mass flow rate and adjusting the collector at different angles.

2. MATERIALS AND METHODS

The collector is situated in the LAUTECH, specifically situated at the Mechanical Engineering Department of the university. The collector is sourced locally from a segmented mirror and its properties are outlined in Table 1. The installed collector measures 2.1 metres in length and is composed of galvanized steel mounts, parabolic reflector panels made from segmented mirror material that is lightweight, rigid, and precise, a structurally efficient galvanized steel torque tube, a tubular receiver, and a manual tracking system. The specifications of the Parabolic Trough Collector are shown in Table 1.0.

2.1 Construction of Parabolic Trough Collector, PTC

The PTC was created with a straightforward methodology. The parabolic trough system consists of two primary components, namely the receiver and the support structure. The comprehensive elucidation of each component is expounded upon in this particular section.

1. Parabolic Trough: A parabolic shape was formed using plywood with dimensions of 202 cm x 135 cm. The plywood was utilized to impart mechanical stability to the parabolic trough. A macroscopic organism was affixed onto the plywood, upon which a series of 27 segmented mirrors, each measuring 202 cm x 5 cm, were adhered. The segmented mirrors were adhered to a manner that resulted in the formation of a parabolic curve. Segmented mirrors were employed because of their exceptionally high reflectivity of 96%. The reflector consists of segmented mirrors affixed to a plywood substrate.

2. Absorber tube: The absorber tube, composed of Galvanised iron (GI), is positioned at the focal point of the parabolic trough. The length of the Galvanised iron is measured to be 2.21m, while its internal and external diameters are recorded as 0.02905m and 0.03105m, respectively. The utilization of black-coated absorber tubes was employed to enhance the efficiency of solar radiation absorption that is reflected by the reflector.

3. Support Structure: The supporting frame was designed to distribute most of the weight onto the primary support structure to improve collector precision and stability, The structure was designed for easy dismantling and transport. The unit was mounted on a single frame for easy travel. The structure included wheels for easy transportation between the lab and testing regions. A jockey wheel was added to make transporting and placing the device for testing easier. To securely hold the mirror at an angle, a threaded strut was created. Any site must line with the sun. The receiver size was determined by local channel section availability and the desired concentration ratio.

Table 3.1 Dimension of the Collector

Descriptions	Black Coated (GI)
Rim Angle(ϕr)	90°
Focal Length(f)	0.30 m
Aperture width (Wa)	1.20 m
The outer diameter of GI (Do)	0.031m
The inner diameter of GI (Di)	0.029m
Length of the cylindrical trough(L)	2.1m
Effective Aperture Area (Aa)	2.42m^2
Concentration Ratio(C)	11.7
Reflectivity of the collector (ρ)	0.9
Absorptivity of the GI ($\propto$)	0.95
Transitivity of the GI (τ)	0.8
Intercept factor (Y)	0.92

The authors conducted experiments utilizing the devised parabolic trough collector system as a heat source for heating receivers as presented in Figure 1.0

Figure 1.0 Parabolic Trough Concentrator

2.2 Experimental Set-Up

The experiment involved the use of steel receivers with a focal point of 30 cm, with three different volume flow rates of 0.0004m^3/s, 0.0008m^3/s, and 0.0012m^3/s, and collector inclination angles of 75°, 90°, and 105°. The system was installed in a north-south orientation within the Department of Mechanical Engineering at Ladoke Akintola University of Technology (LAUTECH), located in Ogbomoso, Nigeria. The geographical coordinates of the installation site are latitude 8.1227° N, and longitude 4.2436° E, with an elevation of 347 metres. A 12-channel temperature recorder equipped with thermocouples was employed to measure the temperatures of several components inside the system, including the ambient temperature, reflector temperature, receiver's outer temperature, and interior temperature. The intensity of solar radiation was recorded using a solar radiation metre, whereas the measurement of relative humidity was measured using an environmental metre. Measurements were collected at regular intervals of 2 minutes, spanning from 9 a.m. to 4 p.m.

Data was collected for one representative day to assess the effectiveness of the PTSC system. Concurrently, the temperature recorder was utilized to measure and record the fluctuations in ambient, reflector, outer, and inner temperatures at various locations within the trough. The data were collected to assess the effectiveness of the system that was built. The experimental setup of the system is depicted in Figure 1.0.

2.3 Performance of Parabolic Trough Collector

The performance analysis is to establish a thermal characterization of the solar field under varying operational scenarios, including solar radiation, ambient temperature, mass flow rate, and the single-axis sun tracking mechanism employed by the system being investigated. The metrics employed for performance estimation encompassed the solar field thermal efficiency, usable heat production from the solar field, the mass flow rate of the fluid, and the tracking position of the receiver.

Thermal Efficiency: The overall efficiency η_c of solar collectors is typically defined as the ratio of the collector's usable output Q_u to the incident global energy, Q_s, as presented in equation (1)

$$\eta_c = \frac{Q_u}{Q_s} \qquad (1)$$

the useful output Q_u for a concentrating collector, is expressed as shown in (2)

$$Q_u = \text{m Cp}.(T_O - T_i) = A_a.I_b.\eta_o - A_{abs}.U_i.(T_{abs} - T_a) \qquad (2)$$

Where,
m is the mass flow rate
C_p is the specific heat of water at room temperature is 4.18 kJ/kg°C
T_O is the outlet temperature,
T_i is the inlet temperature.
Q_s is the incident global energy, it is the product of incident global irradiance (I) on the collector aperture area (A_a) as written in equation (3)

$$Q_s = A_a.I_b \qquad (3)$$

$wher Aa$ is Effective Aperture Area, (2.42m^2) and the global irradiance I incident on the collector aperture area was measured using a solar meter, [W/m^2]

The estimation of useful energy, denoted as Qs, is determined through the utilization of equation (4).

$$Q_S = \text{m}C_p(T_2 - T_1) \qquad (4)$$

The determination of unused heat, H_L was accomplished by employing equation (5).

$$H_L = Q_{S-}Q_U \qquad (5)$$

Where A_a is the aperture area
I_b is the solar intensity
m is the mass flow rate
Cp is the specific heat capacity
T_2 is the outlet temperature
T_1 is the inlet temperature
T_5 is the ambient temperature.

Mass flow rate formula related to the collector flow rate using equations (6-7)

$$Q_{out} = \dot{m}C_p\ (T_{out} - T_{in}) \qquad (6)$$

$$\dot{m} = \rho\dot{V} \qquad (7)$$

ρ is the density of water at room temperature is *998.2 kg/m*^{3}
$\dot{V}$ is the volume flow rate
$\dot{m}$ is the mass flow rate

3. RESULTS AND DISCUSSIONS

The thermal effectiveness, temperatures, and usable energy of the Parabolic Trough Collector (PTC) were analyzed at the engineering workshop of LAUTECH, Ogbomoso. The study aimed to examine the influence of mass flow rate, and weather factors on the thermal efficacy, temperatures, and usable energy of the Parabolic Trough Solar Concentrator system', as well as evaluate the effect of tilt angle on the thermal performance of the PTC. Figure 1.0 presents the outlet temperature (T1) against Time at a varying mass flow rate. It can be inferred that the outlet temperature, denoted as T1, reached its highest value when the mass flow rate (m_3) was 0.0012m^3/s over the whole of the experimental period. The temperature increment at the inlet, denoted as T_2, is evident in Figure 2. It is observed that the temperature increment remained consistent and stable when the mass flow rate was 0.0012 m^3/s (cubic metres), indicating its effectiveness at this particular mass flow rate for achieving the desired inlet temperature.

The outlet temperature distribution of the PTC (Parabolic Trough Concentrator) at various mass flow rates is shown in Figure 1. It shows that the thermal value at a mass flow rate, m_3, of 0.0012m^3/s has the highest temperature distribution, In contrast to the fluctuating changes shown at mass flow rates of 0.0004 m^3/s and 0.0008 m^3/s for mass flow rates, $m_{1,}$ and m_2, respectively,

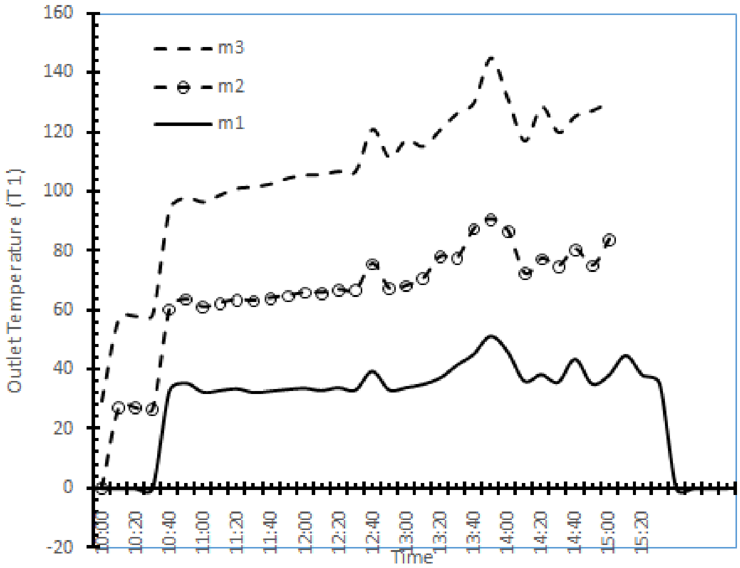

Figure 1.0 Graph of Outlet Temperature (T_1) against Time at a varying mass flow rate

Figure 2 displays the inlet temperature distribution of the Parabolic Trough Concentrator (PTC) at different mass flow rates. The thermal value at a mass flow rate, m_3 of 0.0012m^3/s exhibits the most significant temperature distribution. In contrast, the temperature distribution at mass flow rates of 0.0004 m^3/s and 0.0008 m^3/s for mass flow rates m_1 and m_2, respectively, demonstrates fluctuating changes.

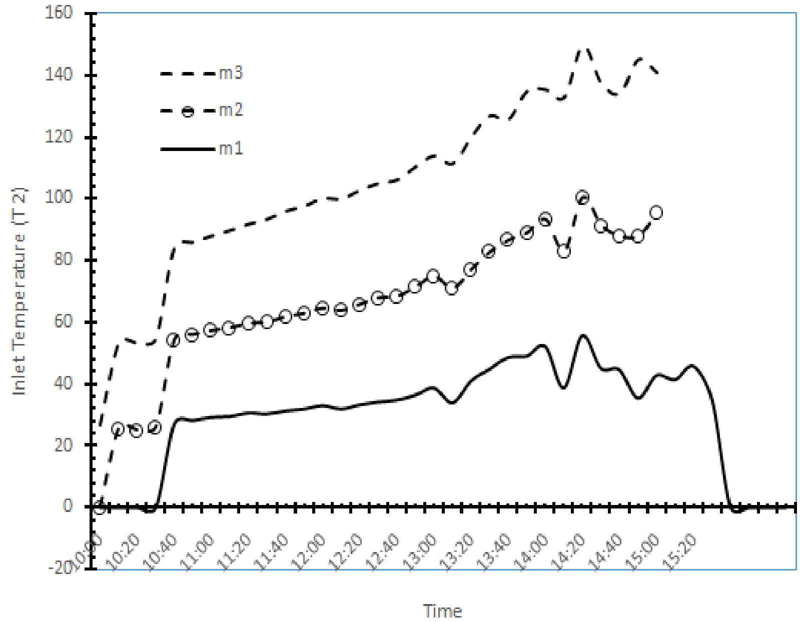

Figure 2.0 Graph of inlet Temperature (T_2) against Time at a varying mass flow rate

The impact of weather conditions on the temperature distribution of the Parabolic Trough Solar collector's working fluids is elucidated in Figure 3.0. The observed fluctuations in the outlet, (T_3) inlet (T_1), receiver, surface collector,(T_2), and absolute temperatures, (T_5), as depicted in Figures 3.0. Primarily arise from the daily weather conditions, which impact the temperature of the PTC system. These graphs illustrate how the presence of cloud cover between the sun and the earth affects thermal distribution, as well as how varying atmospheric conditions of water content in the air impact the performance of the PTC system.

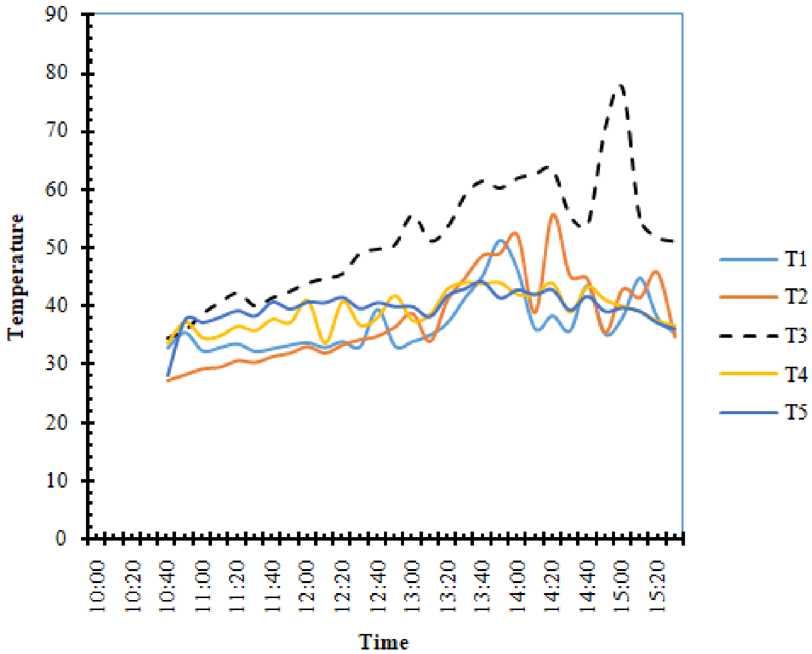

Figure 3.0 Graph of temperature against time

Figure 4 depicts the Parabolic Trough Concentrator (PTC) inlet temperature versus time as the inclination angle varies. It demonstrates that the thermal value is greatest at a tilt angle of 90 degrees, in contrast to the fluctuating variations observed at tilt angles of 30 degrees and 105 degrees, respectively.

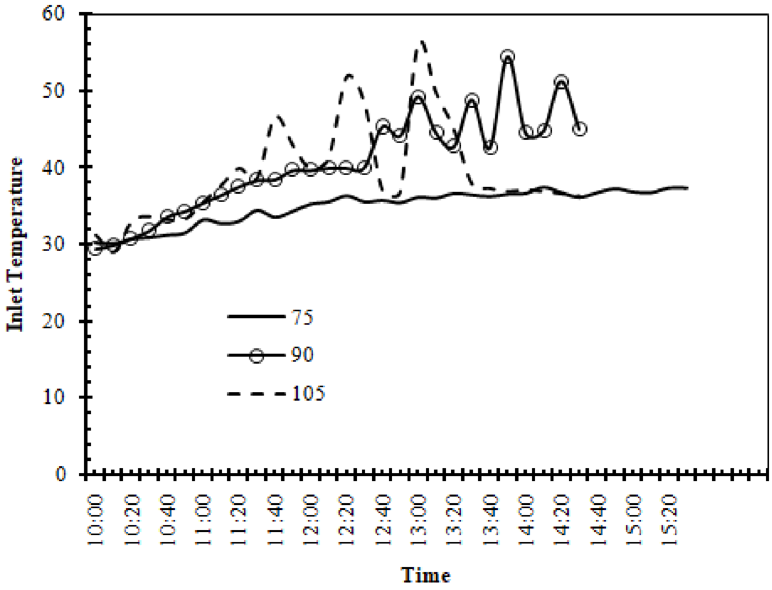

Figure 4.0 Graph of inlet temperature against time at a varying tilt angle

Figure 5 shows the PTC outlet temperature versus time as the inclination angle changes. It indicates that the thermal value is greatest at a tilt angle of 90 degrees, as opposed to the fluctuating changes observed at tilt angles of 30 degrees and 105 degrees, respectively.

Figure 6 depicts the temperature of the PTC receiver over time as the inclination angle changes. It shows that the thermal value is at its highest at a tilt angle of 90 degrees, in contrast to the fluctuating fluctuations seen at tilt angles of 30 degrees and 105 degrees, respectively.

Figure 7 illustrates the relationship between usable and unused energy over time, with an average unused energy of 1000 J and an average unused energy of 1500 J. This suggests that there is a greater amount of energy available for utilization.

Figure 8.0 illustrates the effect of meteorological conditions; solar intensity and time on the thermal efficiency of the Parabolic Trough Solar collector's working fluids. As depicted in Figure 8, the observed variations in solar intensity determine the pattern of the thermal effectiveness. Variations in thermal efficiency with solar intensity and time, which impact the performance of the PTC system, are caused predominantly by daily weather conditions. These graphs illustrate the impact of cloud cover between the sun and the earth on thermal efficiency, as well as the impact of varying atmospheric conditions on the efficacy of the PTC system. The calculated average solar intensity and efficiency for the PTC were 400 W/m^2 and 40%, respectively as shown in Figure 8.0.

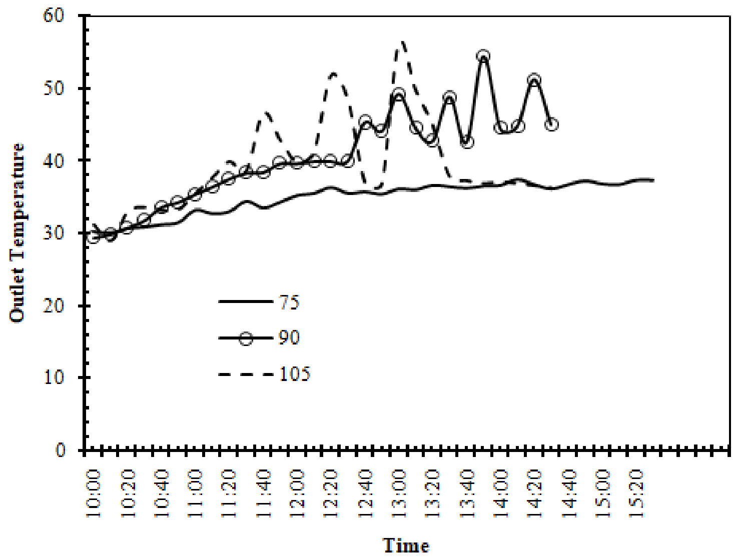

Figure 5.0 Graph of outlet temperature against time at a varying tilt angle

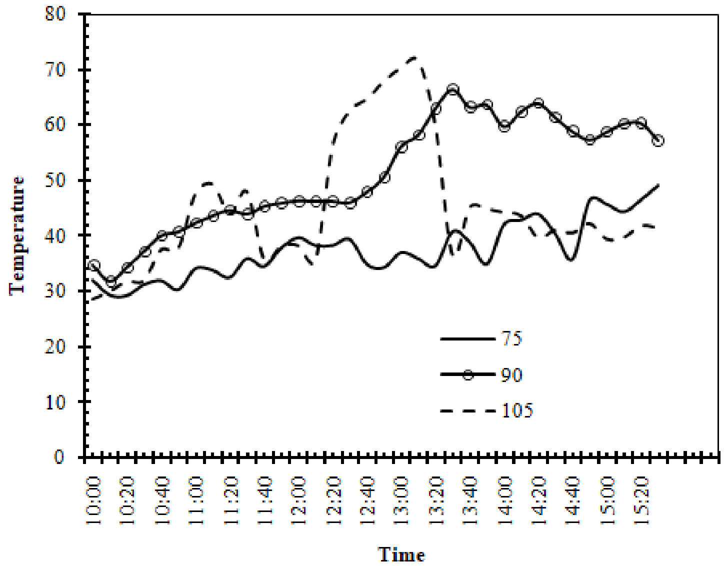

Figure 6.0 Graph of receiver temperature against time at a varying tilt angle

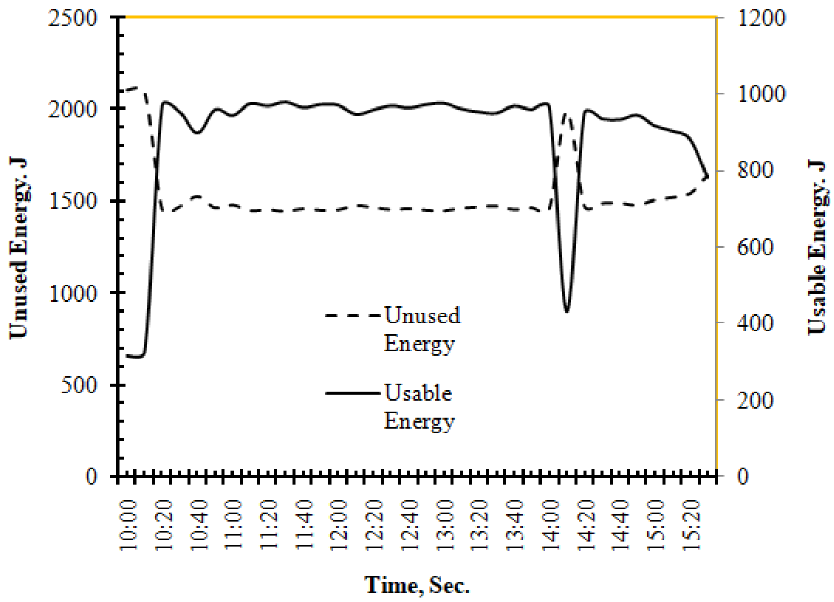

Figure 7.0 Graph **of Usable and Unused Energy against time**

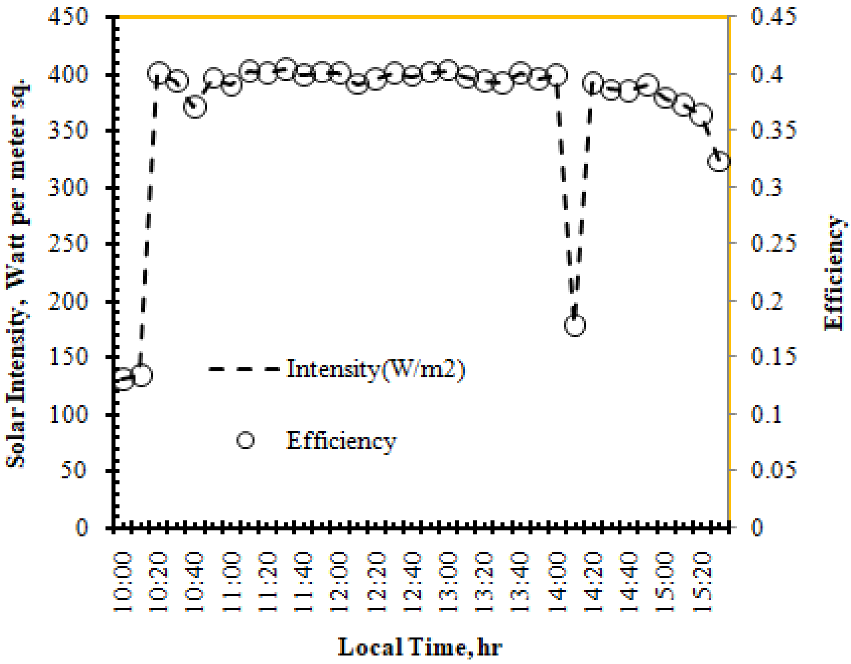

Figure 8.0 Graph of Intensity and efficiency against time

4. CONCLUSIONS

Fossil fuels have been the primary source of energy for the vast bulk of human civilization. The utilization of fossil fuels entails adverse repercussions, such as a rise in carbon dioxide (CO_2) emissions. Solar energy is widely regarded as a very promising alternative energy source due to its significant potential to fulfill a substantial amount of global energy demand. The efficacy of parabolic trough solar collectors is contingent upon several operational and meteorological parameters. This study gave an experimental analysis to examine the impact of tilt angle and mass flow rate on the operational efficiency of a parabolic trough solar concentrator.

An experimental examination was performed on a parabolic trough solar collector at the Engineering workshop of LAUTECH in Ogbomoso. The system is equipped with a 1.2-meter aperture width, a 2.1-meter collector length, an adjustable rim angle of 75º, 90º, and 105º, a focal length of 30 cm, a 10-liter storage tank, and a flow metre. In this study, a 12-channel temperature recorder, namely an SD data logger, was employed to assess the temperatures of various points including the inlet, outflow, ambient, receiver, and collector. Solar radiation measurements were conducted using a solar metre throughout six hours, from 10 am to 4 pm, with readings taken at 10-minute intervals. The working fluid employed in this study was water. Following the collection of data, a thermal performance analysis was conducted to determine the influence of tilt angle, mass, and flow rate on the efficacy of the solar concentrator.

The findings revealed that the system demonstrates enhanced thermal performance with meteorological variables, including sun intensity, usable energy at an increased mass flow rate, and a tilt angle of 90º. This device offers a measure of reducing dependence on electricity generation and mitigating the adverse effects of fossil fuel combustion, hence resulting in a reduction of environmental and public health concerns.

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Conflict of interests

The authors declare no conflict of interest.

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