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Development and Performance Evaluation of a Linear Fresnel Concentrator for Heating Water

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ABSTRACT
Linear Fresnel Concentrator is a type of solar concentrator that uses a series of flat or slightly curved mirrors to focus sunlight onto a linear receiver tube. "The Development and Performance Evaluation of a Linear Fresnel Concentrator (LFC) for heating water was evaluated." The LFC system utilizes locally sourced materials to develop the solar tracking system, automated control and a water heating system to optimize energy output. Performance evaluation results shows hourly readings of the ambient, absorber and reservoir temperatures which were recorded between 9:00 am and 04:00 pm but between the hours of 12:00 pm and 4.00 pm, hot water temperatures of above 50ºC were achieved. Moreover, the maximum hot water temperature achieved was 96.69ºC while the peak hot water temperature was 93.98ºC and a thermal efficiency of 40.27%. Readings were taken for a period four days. Hence, the automated LFC system demonstrates the potential for cost-effective and sustainable water heating, particularly in regions with high solar irradiance.

INTRODUCTION

Technology can be used to harness solar energy for heat and electricity generation operating based on the principles of concentration and thermal energy conversion (Muhammad and Yahaya 2016). Concentrated Solar Power technology has been around for some decades now. LFRs were developed for large-scale solar thermal power generation that results in thermal capacities of at least several tens and up to many hundreds of MW. When scaled down, the Linear Fresnel reflectors meet the medium temperature ranges (100 °C – 250 °C) for the generation of domestic and industrial process heat (Ayadi and Al-Atari 2014). Much investments have been made in recent times on developing this technology.

LFC technology was conceived by Augustin-Jean Fresnel (1788-1827) and used in the optical system of marine indication headlights (Ghodbane et al 2016). Giovanni Francia (1911–1980), designed the first prototype of linear Fresnel concentrator with the downward facing aperture covered with glass honeycomb tubes in 1962, with an efficiency of 60 % and was able to generate steam with temperature equivalent to 450 °C (Ghodbane et al 2016). For instance, NOVATEC BIOSOL (a German company) built the first commercial linear Fresnel reflector plant in the world, situated in Spain. These opportunities are becoming more apparent as new grid technologies like Linear Fresnel Concentrator (LFC) is emerging and competitive with traditional/conventional power generation methods available. The LFC works with the principle of concentrating solar power (CSP) technology in that the incoming beams from the sun rays are concentrated by specially designed optical devices to heat a fluid then extract work from the fluid using a heat engine.

Presently, the demand for energy and the inadequate supply of fossil fuels has added a huge burden on human existence (Quadrelli and Rouquette, 2020). The use of fossil fuel as primary source of energy has led to both health and environmental challenges as indicated by the Intergovernmental Panel on Climate Change (IPCC) (Muhammad et al 2021). This has led to the deployment of renewable energy such as solar, wind, biomass and geothermal energies necessary to meet the global increase in energy demand (Bleam, 2017). The country has the potentials to improve on its energy generation by adopting solar technology (Gielen et al 2019). The solar energy is one of the most important renewable energies because of its abundance nature and sustainability. This includes the production of both electric and thermal energy (Kumar et al 2020). Local indigenous industries could benefit from thermal energy produced directly from concentrated sunlight (Gielen et al 2019). Large scale Solar power technologies operates ideally in dry regions where urban development is scarce and land is readily available ((Hernandez and Allen 2016). Nigeria geographically, is blessed with abundant solar energy that can be harnessed via many technologies. An important aspect of solar is the utilization of the Linear Fresnel Concentrator (LFC) (Kumar et al 2020 and Prakash, 2019).

Linear Fresnel Concentrator is a type of concentrating solar power (CSP) technology used to harness solar energy for heat and electricity generation (Muhammad et al 2016,). It operates based on the principles of concentration and thermal energy conversion(Ghodbane et al 2016).The use of LFC offers a cost effective and scalable solution for harnessing solar energy and converting it into heat and electricity, industrial process and water desalination. They are particularly well suited for regions with high direct normal irradiance and ample land availability (Sark and Cororna 2020). Overall, the use of Linear Fresnel Concentrators aligned with the global transition towards clean, renewable energy sources and reducing greenhouse gas emissions also offers a viable solution for meeting growing energy demand while addressing environmental challenges (Muhammad et al 2020).

The method of concentrating sunlight as well as the type of heat engine used defines the type of solar thermal technology (Belgasima et al 2018). The two most common methods of concentrating solar radiation are line focusing and point focusing (Singh, 2017). Parabolic trough plants are the most developed of the CSP technologies and the majority of plants installed worldwide are of this type. They offer an acceptable performance level but some limitations do still exist. The curved mirrors are relatively expensive and aspects such as the need for flexible couplings and strong foundations to combat wind loads result in a high cost per kWh. The potentials for future cost reductions is also limited (Singh, 2017). Linear Fresnel Collector (LFC), are comparatively new and offers much potential with better reduction in cost. It is not as efficient as the parabolic trough but is projected to have a lower investment cost per kWh. The technology also uses simpler parts that could be manufactured locally (Sun et al 2021). Using renewable energy at domestic level could also offer energy independence for the majority with presently limited or zero access to reliable energy. Solar radiation reaches the atmosphere from the Sun, however, radiation level drops with the square of the distance to the sun as explained by (Muhammad et al 2016).

The aim of this work is to design, construct and evaluate the performance of an automated Linear Fresnel Concentrator for water heating.

MATERIALS AND METHODS

Materials

The following materials were used for the study; a 1.5mm aluminum sheet and galvanized sheet, reflective mirrors, Clips, bolt, screws, nuts and thread fasteners, Gum and Angle irons.

The equipment used in this research work are shown in Table 1.

Table 1: List of Equipment Used

S/NO	Equipment	Specifications	Model
1.	Chain sprockets	Pitch:8mm Length:0.5m Teeth:15	CSP-ALFC-5M-D
2.	Servo motor	32V, 3A	T66001
3.	Motor Driver	12V, 2A	T66001
4.	Arduino Mega	16 MHz	2560
5.	LCD screen	(20 x 4)	HD44780
6.	Pump	DC pump	QR30E
7.	Battery	12V, 7AH	Homaka

Methods

Construction of the Linear Fresnel system

A mild steel square pipe iron sheet of 30 x 30 x 1.5 mm was cut into the required dimension by a hacksaw to form the support frame of the system. The shapes were outlined on the metal initially using a scriber and then manually cut with the hacksaw. The support frame was welded together with a steel pipe with stainless steel electrodes. The interior frame also was cut from the square mild steel pipe of 30 x 30 x 1.5 mm which supports the reflective mirrors. Holes were created using a hand drilling machine for where bolts and nuts will be used for fastening (Ahire et al 2016). A total number of 5 flat mirrors of 220 x 640 mm dimension were fixed horizontally to ensure that it redirects the sun rays towards a chosen focal point where the absorber tube is located. A galvanised sheet of maximum length 700 mm and a 330 mm width was folded in the form of a ‘U’ geometry to form the trapezoidal cavity that helps to add upon the rays that come directly from the mirrors (Ahire et al 2019).

The outside vacuum space of the cavity was laced with polystyrene sheet to prevent heat loss that is meant for heating. An aluminium tube was used to form the absorber tube as they have good thermal transfer coefficient properties and coated with solar selective coating. Afterwards, a 2 mm flat mild steel bar that links the drive mechanism (comprising of sprocket and chain to the mirrors. Fasteners nuts, bolts and screws were used to hold the Machine user interface by the side of the frame (Ghodbane et al 2016). The storage tank made of aluminium sheet was coated internally and lagged with fibre glass for insulation. A hose of maximum length 1300 mm was connected to the 50 litres storage tank. The tank was sealed with a pump that circulates the water to be heated through the system (Samson, 2013,). Finally, the system was setup for initialization to process the production of hot water. Some of the various processes and assembling are captured below in plates I, and II.

Plate 1: Constructed Structure of the Exterior and Interior Frames

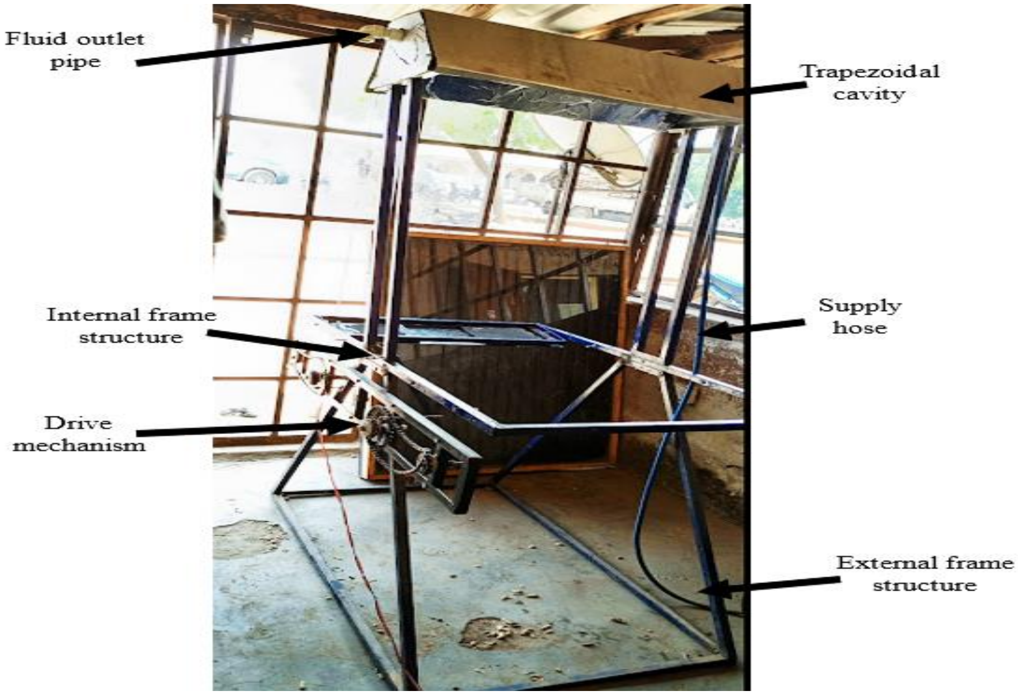

Plate 2: Schematic Presentation of Linear Fresnel Concentrator

Performance Evaluation

The following were used to determine the performance evaluation of the LFC.

i. The collector energy losses
ii. The solar energy absorbed by the working fluid
iii. The heat removal factor
iv. The thermal efficiency

Determination of Collector Energy Losses: This was determined using equation (1) (Singh et al 2014)

$$Q_{loss} = U_L A_C (T_p - T_a) \quad (1)$$

Where, $U_L = \frac{1}{\frac{t_b}{k_b} + \frac{1}{h_{c,b-a}}} \quad (2)$

Applying equation (1): we obtain:

$Q_{loss} = 0.6 \times 0.231 \times (331.13 - 269.27)$

$Q_{loss} = 0.1386 \times 61.86$

$Q_{loss} = 8.573$ W

Determination of Solar Energy Absorbed by the Working Fluid: This is obtained using equation (3).

$$Q_u = [A_c \rho \alpha I - A_a U_L (T_p - T_a)] \quad (3)$$

Where,

Q_u is energy collected from solar concentrator in W

$A_c = 0.231 m^2$

r = 0.025 m

A_a is area of aperture in $m^2 (A_a) = \pi r^2$

A_a= 3.142 × 0.025² =0.00196

A_a=0.00196 m^2

ρ is reflectance of receiver/basin = 0.68

α is absorber transmissivity = 0.88

τ is the absorber absorptivity= 0.96

U_L is the overall heat loss coefficient = 0.6 W/m²K

$T_p = 331.13$ K

$T_a = 269.27$ K

I is the solar irradiance of Kaduna for 2006-2015 = 282.61 W/m^2

The overall solar energy absorbed i.e. overall thermal gain can be calculated using equation (3);

$$Q_u = [0.231 \times 0.68 \times 0.88 \times 282.61 - 0.00196 \times 0.6 \times (331.13 - 269.27)]$$

$Q_u = 39.07 - 0.073$

$Q_u = 39$ W

Determination of Heat Removal Factor: The heat removal factor is obtained using equation (4) (Malvi, C. S., Gupta, A., and Gaur, (2017).

$$F_R = \frac{\dot{m} c_p}{A_c U_L}\left[1 - exp\left(-\frac{A_c U_L F'}{\dot{m} c_p}\right)\right] \quad (4)$$

Where

$\dot{m}$ is the mass flow rate as shown in equation (5)

$$\dot{m} = \rho A V \quad (5)$$

c_p is the specific heat capacity of water = 4,200 J/kg K (Samson, 2013)

ρ is the water density = 1000 kg/m^3

A is the pipe cross sectional area in m^2= 0.01m^2

V is the velocity of flow = 1.23m/s^2

Flow rate = 0.000123 m^3/s or 0.123 kg/s.

$A_c = 0.231 m^2$

U_L is the overall heat loss coefficient = 0.6 W/m²K.

F' is the collector efficiency factor =0.9 was adopted for this study.

A 12 V pump was used to pump the working fluid (water) around the system, the flow rate was obtained experimentally by observing the time it takes for a specified quantity of water to completely transfer to a new container (Samson, 2013). Applying equation (5), we obtained:

$\dot{m} = 1000$ x 0.01 x 1.23

$\dot{m}$ = 0.123 kg/s

Thus, equation (4), we have the heat removal factor as;

$F_R = \frac{0.123 \times 4200}{0.231 \times 0.6}\left[1 - exp\left(-\frac{0.231 \times 0.6 \times 0.9}{0.123 \times 4200}\right)\right]$

$F_R = \frac{516.6}{0.1386}\left[1 - exp\left(-\frac{0.12474}{516.6}\right)\right]$

$F_R = 3727.27[1 - exp(-0.000241)]$

$F_R = 3727.27[1 - 0.9998]$

$F_R = 3727.27[0.0002]$

$F_R = 7.45454$

$F_R = 7.45$

Thermal Efficiency

The thermal efficiency (η) of solar concentrator–receiver system was computed by equation (6):

$$\eta = \frac{[\dot{m} C_p (T_o - T_i)]}{I A_c} \quad (6)$$

Where,

T_o= Temperature of fluid coming out of the collector

T_i = Temperature of the fluid going into the collector both in °C

$$\eta = \frac{[0.123 \dot{\times} 4200 (96.69 - 93.98)]}{282.61 \times 0.231}$$

$\eta = 40.27\%$

Working Procedure

The following were carried out to ensure proper functionality and alignment. The system was turned on to initiate the solar tracker by varying the angles of incidence that can tilt automatically to track the sun after 10 seconds where it will be highly concentrated with the help of two LDR sensors. In order to tilt, it involves a server motor to perform the tracking.

The solar tracker then passes the temperature information to the control unit i.e. Machine User Interface. The control unit then relates the information as regarding the position of the sun at any given time to stepper motor.

The stepper motor comprises of a chain and sprocket network that drives the mirrors adequately all to an angle that was able to concentrate the sun onto the absorber tube.

The stepper motor then pumps water and circulates it from the reservoir through the absorber tube back to the storage tank to heat the working fluid in a continuous cycle.

The microcontroller sensor was used to record the ambient temperature, absorber temperature and the reservoir temperatures with time respectively.

RESULTS AND DISCUSSION

Result for Temperatures

The Linear Fresnel system was tested for a period of four days. The following data were collected from the Linear Fresnel system.

The results for the test conducted are presented in the Table 1. The time and temperatures of the tests conducted were recorded and presented. The following data were collected from the Linear Fresnel system:

Ambient temperatures absorber, and reservoir temperatures were recorded hourly with machine user interface which had three sensors respectively, between the hours of 9:00 and 04.00 pm.

The relationship of the various temperature readings from 9:00 am to 4:00 pm. The ambient temperature of 32.12ºC was obtained at 9:00 am, which is a flat bell shaped and reaches peak at 2.00 pm with a temperature of 35.55ºC. The absorber temperature increases gradually during the start of the day and follows a nearly straight line until it reaches its maximum value of 86.58ºC, and then back down influenced by the lack of quantity of direct solar radiation. The Reservoir temperature rises significantly until it peaks at 2.00 pm and then starts to reduce at 3:00 pm to 4:00 pm due to decline in solar irradiance. This shows the effect on clouds on 11th and 12th January 2024, and 19th February, 2024 is very apparent on the results, the absorber and reservoir temperature dropped at 3:00 pm.

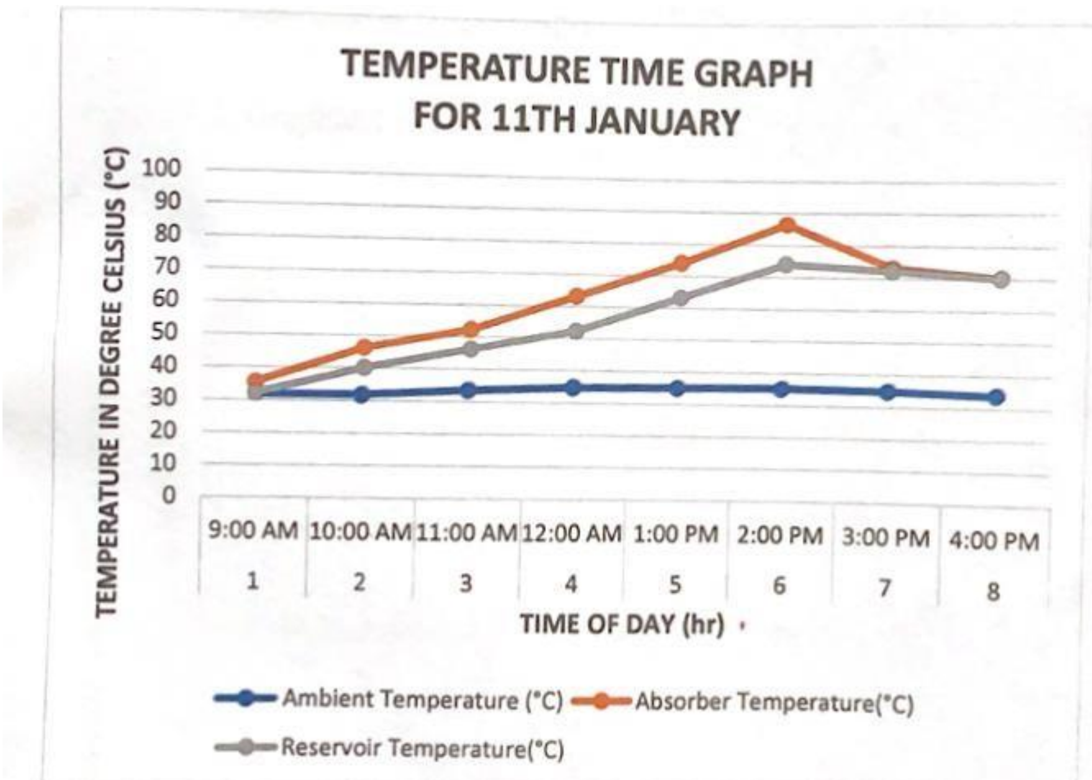

Figure 1: Graphical representation of water temperature for 11th January, 2024

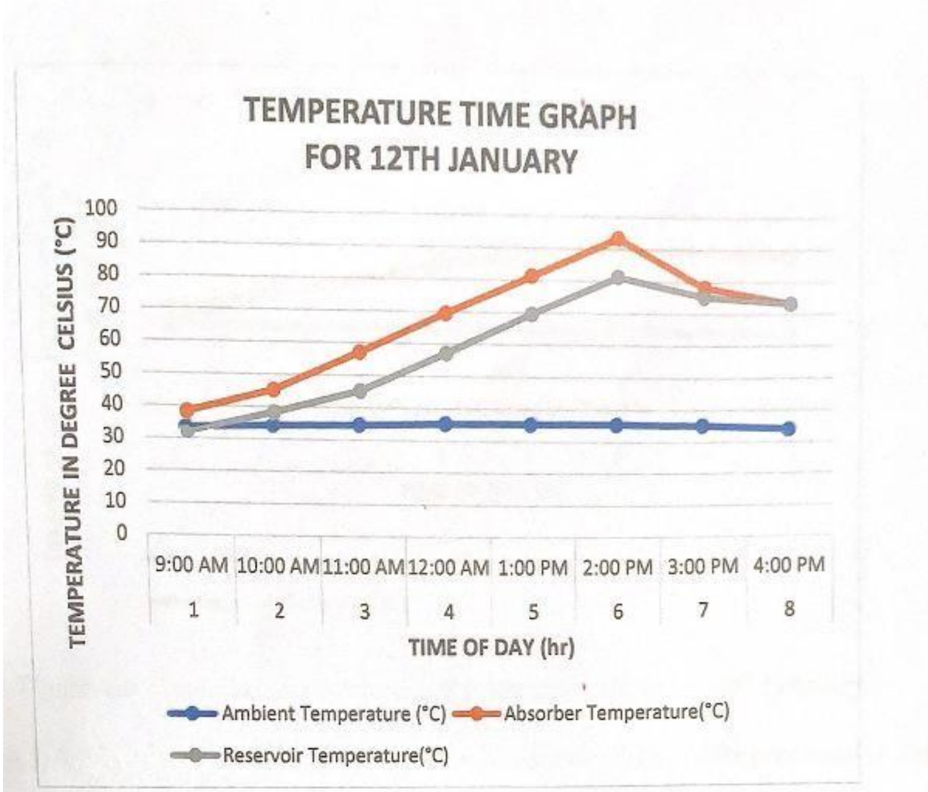

Figure 2: Graphical representation of water temperature for 12th January, 2024

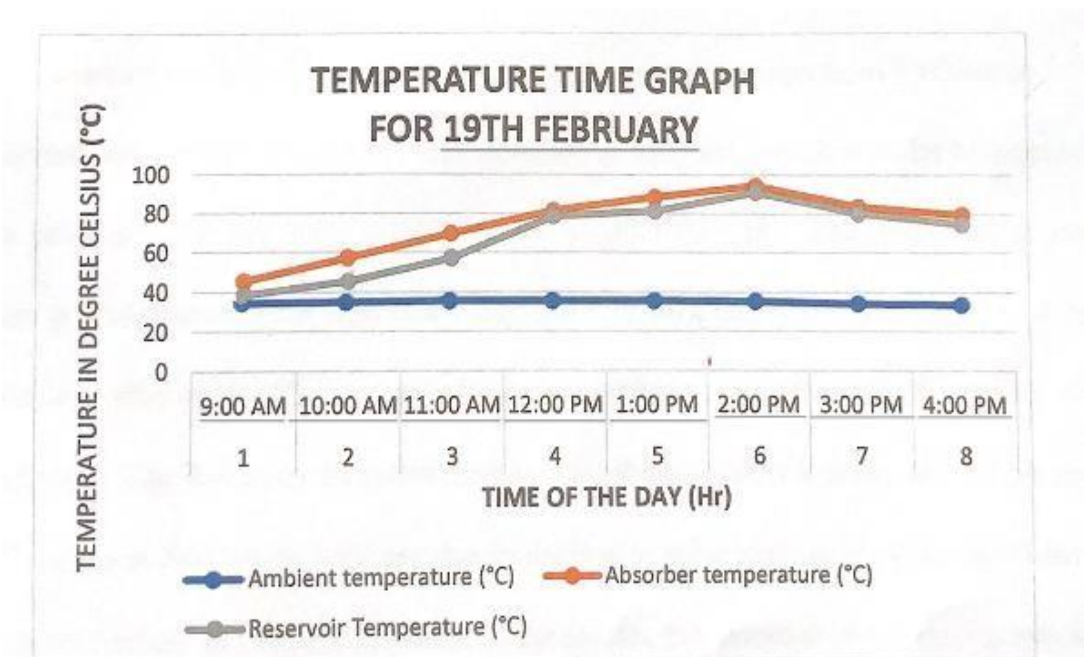

Figure 3: Graphical representation of water temperature for 19thFebruary, 2024

Table 1: Experimental data recorded for the Fresnel system for 20th February

S/NO	Time of the day	Ambient temperature (°C)	Absorber temperature (°C)	Reservoir temperature (°C)
1.	9:00 am	34.93	48.24	40.24
2.	10:00 am	35.65	59.11	55.24
3.	11:00 am	35.66	70.52	67.11
4.	12:00 pm	35.67	83.24	80.52
5.	1:00 pm	35.44	90.22	86.24
6.	2:00 pm	35.21	96.69	93.98
7.	3:00 pm	33.18	92.25	90.11
8.	4:00 pm	33.12	88.14	85.52

Table 1 showed the final test and performance evaluation of the Linear Fresnel system with respect to the temperature results obtained for an eight-hour interval on the 20th February. Hourly readings of the ambient, absorber and reservoir temperatures were recorded between 9.00 am and 4:00 pm. Between the hours of 10:00 and 4.00 pm, hot water temperature of above 50°C was achieved. It was noticed at 1:00 pm that there was a sharp rise in absorber temperature with a temperature of 90.22°C and reservoir temperature of 86.24°C. At 2:00 pm the system experienced the highest maximum rise of absorber temperature which was 96.69°C and a hot water reservoir temperature was recorded as 93.98°C respectively. The temperature peaks at 2:00 pm based on the fact that, sun rays focus more at absorber and gains full concentration. This is traced to the fact that the sun's radiance is always higher during the midday than in the mornings. At the last hour of the test i.e at 3:00 to 4:00 pm, there was a reduction in the absorber and reservoir temperature with results of 88.14°C and 85.52°C, this is due to high loss at that instance from the system. This result shows the effectiveness of the Fresnel system, which is more steady and higher as compared to other days.

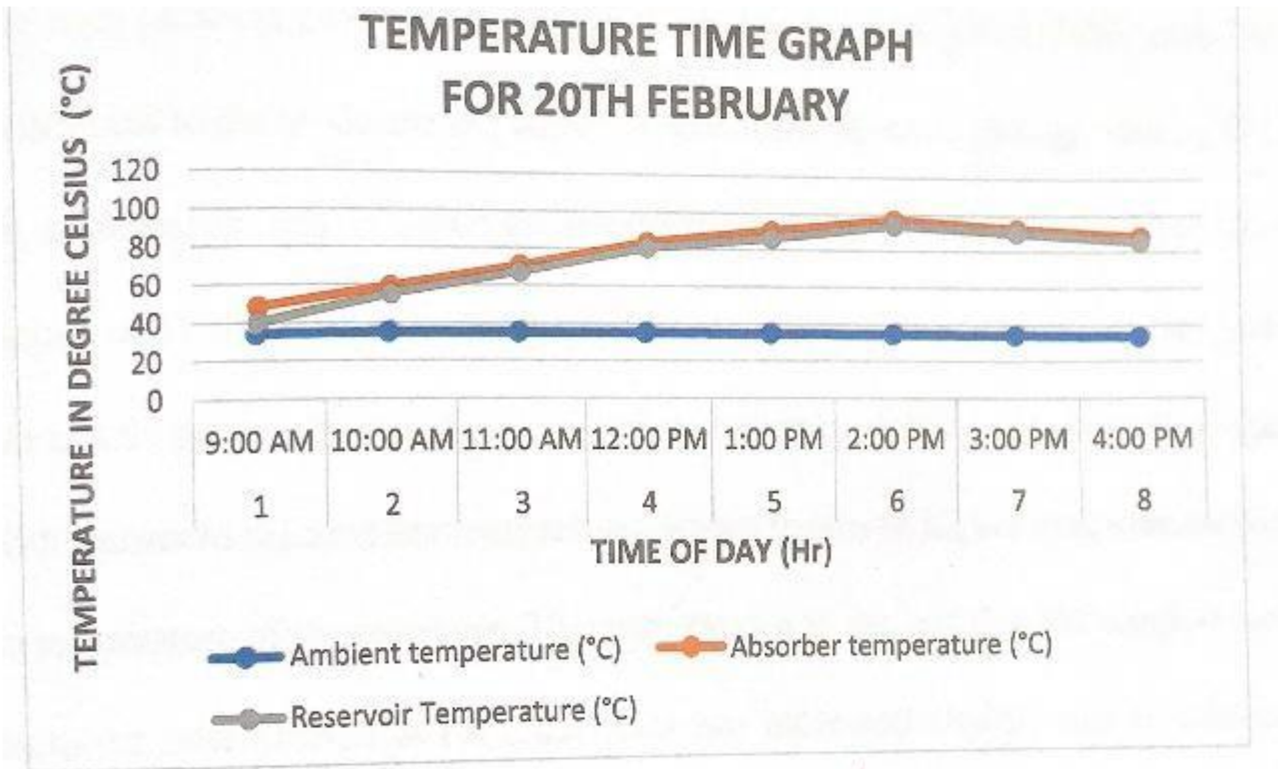

Figure 4: Graphical representation of water temperature for 20th February, 2024

The reservoir water temperature of 93.98°C and thermal efficiency 40.27% of a Linear Fresnel concentrator obtained for the system is far better than the work reported by [Ahire, 2016] which he achieved a maximum water temperature of 71.24°C at midday. Furthermore, [Ghodbane, 2016] was able to achieve thermal efficiency exceeding 29% with a temperature exceeding 74°C. The system was designed with 11 reflecting mirrors of 1500 mm × 1000 mm dimension each to redirect the solar radiation and 4 copper absorber tubes for heat generation. In addition, [Sasmson, 2013]
achieve a maximum water temperature of 73°C and thermal efficiency of 27%.

CONCLUSION

A Linear Fresnel Concentrator system was developed and tested for heating water in Kaduna, Nigeria. The developed automated LFC system is technically feasible in heating water and some regions of Africa since insolation is similar as most of the hot water requirements in society are largely below 60ºC. The results obtained from evaluating the LFC performance shows clearly the hourly readings of the ambient, absorber and reservoir temperatures which were recorded between 9:00 am and 04:00 pm but between the hours of 12:00 pm and 4.00 pm, hot water temperatures of above 50ºC were achieved. Furthermore, the maximum hot water temperature achieved was 96.69ºC while the peak hot water temperature was 93.98ºC and a thermal efficiency of 40.27%. Readings were taken for a period four days. Hence, the automated LFC system demonstrates the potential for cost-effective and sustainable water heating, particularly in regions with high solar irradiance. The study has established that LFC system can also serve as a pre-heater when temperature of more than 60ºC is needed since sunshine is available everywhere in the country and electricity is limited in most part of our region. Linear Fresnel Concentrator system is a viable option for meeting our energy needs and can be more efficient in all other parts of the country.

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