

Design, Fabrication and Performance Evaluation of Hybrid Parabolic Dish Solar Concentrator for Cooking and Heating of Water

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To cite this article:

Mohammed Gwani, Umar Muhammad Kangiwa, Abubakar Gado Abubakar, Sadik Umar. (2023). Design, Fabrication and Performance Evaluation of Hybrid Parabolic Dish Solar Concentrator for Cooking and Heating of Water. *Advances*, 4(4), 137-144.

<https://doi.org/10.11648/j.advances.20230404.14>

Received: October 31, 2023; **Accepted:** November 16, 2023; **Published:** December 6, 2023

Abstract: People who live in rural areas have been heating water and cooking by burning wood as their only source of energy. In addition to seriously polluting the environment, fuel wood poses a major threat to rural residents. This has made it necessary to look for a more environmentally friendly alternative energy source for heating and cooking immediately. Solar energy is now a viable technique for water heating and cooking, there aren't many installations of this technology in rural areas. There are many various kinds and designs of solar cookers and heaters. The design, construction, and performance assessment of a hybrid parabolic dish solar concentrator for heating and cooking are presented in this study. The hybrid parabolic dish concentrator consists of a parabolic dish, an absorber plate, mirror reflectors and galvanized pipes for the water heater. A galvanized pipe is design in a circular form and embedded inside the absorber plate for heating of water. Series of experiment were conducted for the designed system including the no load (stagnation test) and with load test. Results obtained from the study showed that the hybrid parabolic dish concentrator can attain high temperatures values. During the stagnation test, the hybrid concentrator attained 167°C and 142°C for the temperature of the concentrator and the absorber plate temperature respectively at 13:00 pm, while the highest temperature attained when the hybrid solar concentrator is loaded water was 131°C at 13:00 pm. The hybrid concentrator is able to achieve a working efficiency of 26.3%.

Keywords: Solar Energy, Parabolic Dish, Concentrator, Solar Water Heater, Hybrid System

1. Introduction

Modern industrialization and lifestyle choices have led to a significant gap between supply and demand for energy, necessitating a sharp rise in the amount of clean, stable, and reliable energy sources. The excessive reliance on fossil fuels to meet our everyday energy needs has a negative impact on both the environment and human health [1]. A country's ability to develop is largely dependent on its energy supply, which is steady and stable and causes economic decline, poverty, and misery [2]. The most dominant available renewable energy on earth is solar energy, and quantum progress has been made to tap into this green energy option [3]. The key element of sustainable, environmental friendly and cost-effective energy generation is the renewable energy

sources. Recently, the number of research related to applications of renewable energy sources have increased. This is due to the extensive depletion of fossil fuel reserves drove by the high demands of energy [4].

The International Energy Agency (IEA) has revealed that since 2019, there has been a drop in the use of fossil fuels and a rise in the use of renewable energy worldwide. The performance of RE generation technologies, particularly energy conversion technologies, has improved due to the ongoing growth of research on RE technologies [5]. At the moment, solar energy is thought to be among the most important, rapidly expanding, widely used, affordable, and commercially appealing energy sources. Not only is solar energy pollution-free, but it may also be used to lessen reliance on fossil fuels. Solar energy is becoming a practical

technology for water heating and cooking. The integration of solar energy systems in rural environments has enormous potential. [6]. Solar energy has emerged as a promising alternative to traditional fossil fuels for various applications, including cooking and water heating. Figure 1 shows the global share of solar energy consumption year 2022.

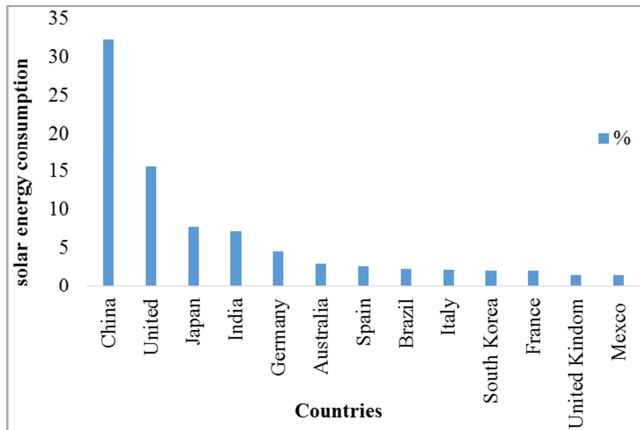


Figure 1. Global share of solar energy consumption year 2022.

1.1. Solar Cookers

Solar cooker is an environmentally friendly device that employs solar radiation to transport heat for cooking, sterilizing, and other purposes through an insulated pot wall. [3]. The solar cookers can be classified into two main categories. The direct and the indirect solar cooker. For the direct solar cooker, sunrays are focused directly into the receiving chamber where the cooking utensil is kept, it is frequently used for cooking purpose due to its cost effectiveness and ease of construction, whereas for the indirect solar cooker a transient fluid transport the heat from the collector to the cooking unit. [3]. The direct type solar cooker is further divided into box-type and the concentrating type. The box-type solar cooker consists of single or multiple glasses covers over an insulated container which is painted black on the inside to maximize heat absorption. On the other hand the concentrating solar cookers employ the principle of optics to concentrate the sunrays on the receiver of the cooking unit where high temperature is generated, it typically uses a parabolic concentrator [7-9]. Parabolic dish solar concentrators are two-axis solar tracking system that focus the sun's rays on the thermal receiver situated at the dish collector's focal point as seen in Figure 2 [10].

Parabolic dish concentrators are a good choice for converting solar energy into usable heat because of their high concentration ratios and accurate tracking capabilities. However, low utilization efficiency and cost-effectiveness are two drawbacks of traditional parabolic dish systems. Numerous studies have evaluated the performance of various solar concentrators and solar cooking technologies. Smith, Johnson [11] Demonstrated the effectiveness of parabolic dish concentrators in providing high thermal energy for cooking. Zhang and Chen [12] Proposed a similar hybrid design and highlighted its potential in maximizing energy utilization.

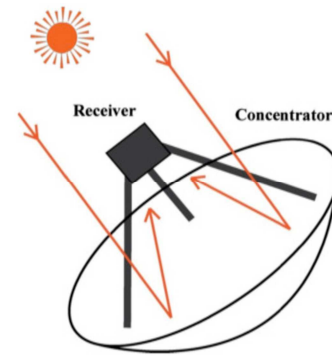


Figure 2. Schematic of parabolic dish concentrator [10].

Hybrid system proposed in this study. Misra, Anand [3] Reviewed the box-style solar cooker and its benefits for energy, the environment, economy, and technological advancement. The writers describe the various kinds of solar cookers and their thermal effectiveness. The design, construction, and performance evaluation of three different types of solar cookers—box-type, panel, and concentrator—was presented by Elamin and Abdalla [13] using materials that could be found locally. The study's findings revealed that, in terms of thermal performance, the parabolic cooker performed the best, reaching an average maximum temperature of 86.5°C, when compared to the box-type 52.4° and the panel-type 43.5°C. Hassan, Kishta [14] Designed and test a box solar cooker for remote area, results from the study showed that the absorber plate stagnation temperatures increased from 113°C to 144°C without a double glass cover and the using reflector the required time for boiling reduces. The performance evaluation and cost economics of developed box type solar cooker was presented by Ramesh, Modi. V. M. [15] the results showed that the first and second figure of merit, standard cooking power, and thermal efficiency of the solar cooker were 0.1084, 0.31, 58.41 W and 37.76% respectively and the payback was found to be 1.08 and 0.49 years respectively when LPG and fuel wood was replaced by developed box type solar cooker. Iwuoha and Ogunedo [16] Presented the performance and economic analysis of a domestic solar cooker the study was able to attain a stagnation temperature of 320°C at a heating rate of 5.4°C/min. with first and second figure of merit of 0.623 m²K/W and 0.464 m²K/W respectively. Komolafe and Okonkwo [17] Presented the design, fabrication and thermal evaluation of a solar cooking system integrated with an Arduino-based tracking device and sensible material (BOSHMS), a maximum temperatures obtained for water, and solar radiation peak is 881.2 W/m², 54°C respectively. Hassan, Kishta [14] Designed, constructed and test a parabolic solar oven. The results obtained from the studies showed that the system can attained highest temperature of 104°C on average sunny day. Gwani, et al., [18] Design, fabricated and experimentally investigated the performance of four reflectors solar baking oven. Results obtained from the study reveals that the cooking time of any food item reduced due to the present of the four reflectors in the design, a highest temperature of 133°C is attained. Yahuza

et al., [19] Design, constructed and test a parabolic solar oven, the results obtained from the study shows that the oven attained a highest temperature of 104°C.

In this study, a hybrid approach that integrates a parabolic dish concentrator with a solar water heater is proposed. The design of the hybrid parabolic dish concentrator involves the combination of a parabolic dish mirror with a central receiver for heat absorption. This hybrid parabolic dish solar concentrator have dual purpose; simultaneously cooking and heating of water. The design will have great advantages such as reducing the cooking/heating time, and increase the overall efficiency.

1.2. Design Equations/Parameter

The hybrid parabolic dish concentrator is designed based on the equation of a parabola given by equation 1.

$$z = \frac{r^2}{4f} \quad (1)$$

Where r is the radius of the concentrator and f is the focal point.

The diameter of the parabolic surface d and the focal distance are related by equation 2;

$$S = \left\{ \left[1 + \left(\frac{d}{4f} \right)^2 \right]^{\frac{3}{2}} - 1 \right\} \quad (2)$$

And the cross-section of the opening is given by equation 3

$$A = \frac{\pi d^2}{4} \quad (3)$$

The focal distance is calculated using equation 4

$$A = \frac{\pi d^2}{16h} \quad (4)$$

The concentration ratio described the amount of light energy concentration achieved by a given collector. It is define as the ratio of the area of the collector aperture A_a to the surface area A_t it is given by equation 5;

$$CR = \frac{A_a}{A_r} \quad (5)$$

Where h is the height of the dish, d is the diameter of the dish, f is the focal point, F is the load, and r is the radius. This is presented in Figure 3.

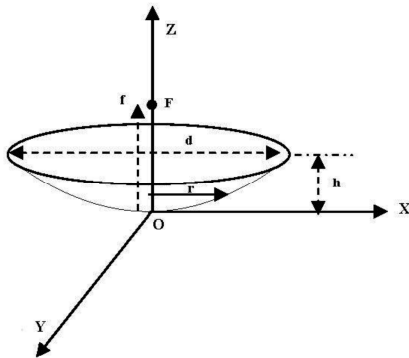


Figure 3. Parabolic dish concentrator design parameters [6].

1.3. Figure of Merit

The figure of merit is a standard procedure for testing the performance of a solar cookers. This figure of merit was proposed by Mullick, Kandpal [20], In this procedure, figures of merit F_1 ($C m^2 W^{-1}$) were determined by conducting the stagnation temperature (without load) and when the system is loaded. The first figure of merit is defined as the ratio of the optical efficiency to the overall heat loss coefficient. It is given by equation 6 [21].

$$F_1 = \frac{\eta_o}{U_L} = \frac{T_{pz} - T_{az}}{I_s} \quad (6)$$

Where $F_{\eta o}$ and F_{ul} is the optical efficiency and overall heat loss coefficient respectively, T_{pz} is the stagnation absorber plate temperature and T_{az} is the average ambient temperature while I_s is the solar radiation in W/m^2 .

The cooking power of the hybrid solar concentrator was calculated using equation 7

$$P = \frac{T_{wb} - T_{wa}}{t} m_w C_{pw} \quad (7)$$

Where; P is the cooking power (W), T_{wb} is the final temperature of water ($^{\circ}C$), T_{wa} is the initial temperature of water ($^{\circ}C$), m_w is the mass of the water (kg) C_{pw} is the specific heat capacity of water (which is 4.16 KJ/kgK).

The thermal efficiency is calculated using equation 8

$$\eta_o = \frac{m_w C_{pw} \Delta T_w}{I_{avg} A_c \Delta t} \quad (8)$$

2. Materials and Methodology

2.1. Materials

The selection of materials needs to be carefully considered in order to build an efficient hybrid solar concentrator. The solar concentrator's materials are chosen for their cost-effectiveness, availability, durability, and thermal efficiency. The materials must be able to withstand harsh weather and inexpensive to maintain and repair. The Parabolic dish concentrator surface was made of iron steel, while the absorber plate was made of Aluminium sheets because of their availability, affordability, and superior corrosion resistance to copper. Other materials used in the construction of the absorber plate included galvanized pipe and tubing for the water flow and reflectors made of silvered glass mirror.

2.2. Design of the Parabolic Dish Concentrator

The design of parabolic dish solar concentrator involves the combination of a parabolic dish mirror with a central receiver for heat absorption. A copper tube with a selective coating as a receiver to improve absorption of solar radiation. The concentration ratio and aperture area are optimized to achieve higher energy collection efficiency [22].

The design of the parabolic dish concentrator was carried out using Solid works software, which contemplates the focus characteristics and the parabola as well as the

dimensions, the geometry and the computer aided design (CAD) is presented in Figure 4 and Figure 5 respectively, while the design specification is shown in Table 1.

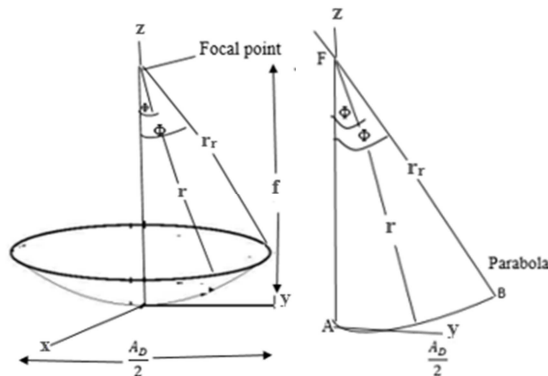


Figure 4. Geometry of parabolic dish concentrator.

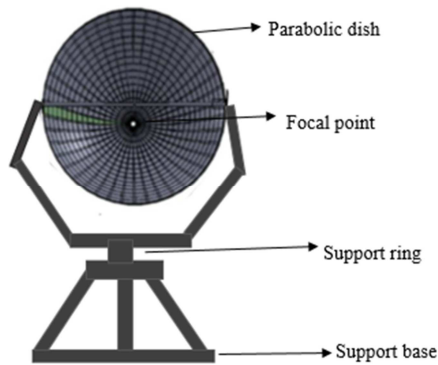


Figure 5. CAD design of the parabolic dish concentrator.

Table 1. Design Specifications.

S/N	Parameter	Value	Units
1	Depth of the parabolic dish	0.15	m
2	Focal point	0.42	m
3	Aperture Diameter	1	m
4	Surface area of absorber	0.08	m

S/N	Parameter	Value	Units
5	Reflector reflectivity material	98	%
6	Support Stand	0,65	m
7	Concentration ratio	52	-
8	Surface area of concentrator	4.0	m ²
9	Rim angle	50	o

2.3. Design Description

The parabolic dish concentrator consists of a receiver, mirror reflectors, and galvanised pipe work to carry the heat transfer fluid. The plane mirrors was cut into smaller 5 cm square size and stick to the inner surface of the parabolic dish, the glass mirror has high reflectivity and thickness of 0.004. The galvanised tube/ passage was attached mechanically to the surface of absorber plate in the parabolic dish concentrator, inside the absorber plate is a circular coil where the water will circulate after passing through the galvanised pipe, a water tank was placed at the side of the receiver where circulation of water is allowed after passing through the copper tubes inside the absorber plate.

The design of the hybrid parabolic dish solar concentrator is optimized to achieve maximum sunlight concentration. The parabolic dish may be continuous or consists of discrete elements to confirm the shape of parabola. The receiver (absorber plate) is attached to the support system placed at the top end of the concentrator, so that the sun is monitored by both the dish and the receiver. The shadow can be minimized by optimizing the size of the receiver, and its support structure can built on the concentrator. The frame of the parabola is made of stainless steel. Aluminium sheet was used as the absorber plate, the thermal conductivity of the aluminium sheet is 205 W/mK, and its thickness is 0.01 mm respectively. To provide high radiation and absorb large amount of heat into the heating chamber the aluminium sheet was coated with black colour. The complete description of the system is presented in Figure 6.

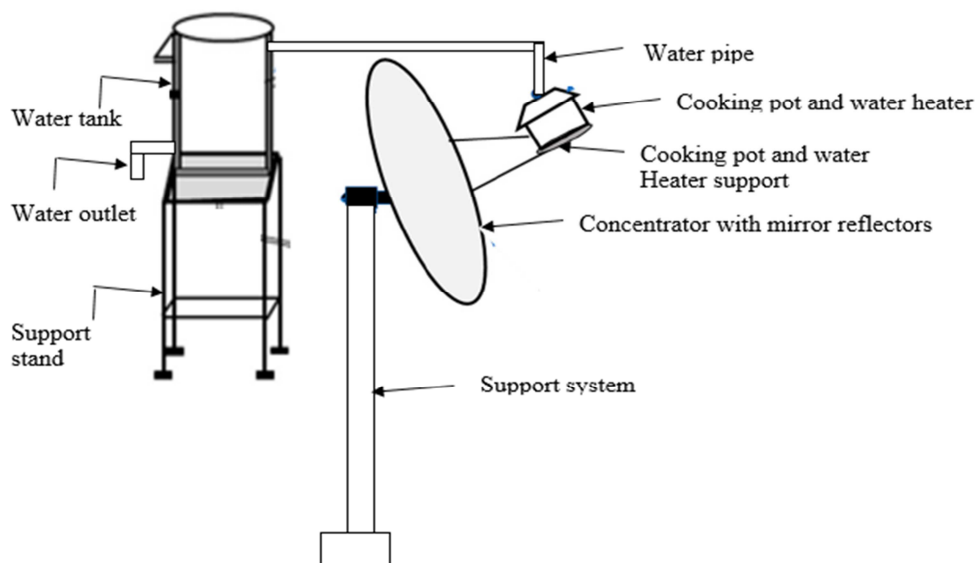


Figure 6. Isomeric view of design description of the complete system.

2.4. Fabrication Process

The fabrication process is described in detail, covering the step-by-step construction of the hybrid parabolic dish concentrator. The fabrication process involves precision shaping and assembly to ensure accurate alignment of the reflective components. Each component's role and the assembly procedure are outlined, ensuring reproducibility and scalability of the concentrator design. The fabrication process includes the construction of the parabolic dish, mirror reflectors using cost-effective materials. The central receiver is assembled with precision, ensuring proper alignment and sealing. The fabricated Aluminium pot and parabolic dish concentrator is as shown in Figure 7 while Figure 8 shows the complete system.

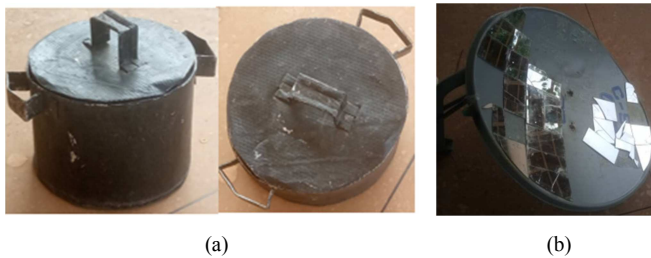


Figure 7. (a) Absorber plate, (b) parabolic dish coupling.

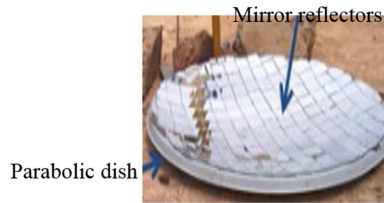


Figure 8. Fabricated solar concentrator.

2.5. Experimental Procedure

The performance evaluation of the HPDSC is carried out under varying solar conditions. The experiment was conducted at the Faculty of Physical Sciences, Kebbi State University of Science and Technology Aliero. The testing site is situated at the Latitude $4^{\circ} 19' 75''$ and Longitude $12^{\circ} 45' 39''$. The performance of the parabolic dish concentrator was investigated by measuring the stagnation temperature and conducting some cooking trials. The tests were conducted in two cases; the case of no-load and load condition. The purpose of the no-load condition was to access the performance of the system before adding load and the concentrator was loaded with food items and water. For the case of the load conditions, time required for cooking a given quantity of meal or boil water was determined using sensible heat test. Measurements were taken at intervals of 30 minutes, for both the no-load and load conditions, and throughout the effective period of sunshine hours at about 8:30 am to 16:00 pm local time. Copper-constantan thermocouples with accuracy of 0.05°C were used to measure the stagnation air temperature inside the concentrator surface. Other parameters measured during the testing include; the ambient (T_a), and absorber plate (T_p) temperature, and wind speed.

3. Results and Discussion

The developed system was subjected to series of experimental test and its performance was evaluated based on its technical and economic viability as a cooking system. Key performance metrics such as solar-to-thermal conversion efficiency, cooking rate, and temperature rise of the water in the solar water heater are measured and analyzed. The results obtained from the performance evaluation are presented and analyzed in the figures. The performance parameter is first figure of merit (F1), efficiency, and cooking power.

3.1. Stagnation Test

Figure 9 shows the variation of ambient temperature (T_a), temperature of the concentrator (T_c), solar radiation, wind speed (V), and temperature of the observer (T_a) against time when the solar concentrator was not loaded. The experiment began at 8:30 am local time to 16:00 pm and lasted for a period of 7 hrs 30 min. From the figure it can be observed that T_c and T_p have similar trend where the values increases with time until a peak value is achieved. However, the wind speed fluctuate in the morning hours until it reaches it a value of 1.6 m/s at exactly 13:00 pm when the sun is directly overhead. It can be seen from the figure that the peak T_c is 148.2°C at 13:00 pm while the T_p has attained a maximum value of 139.5°C obtained at 13:30 pm local time. Similarly the solar radiation has a maximum value of 1150 w/m at 13:00 hrs with maximum T_a of 36°C obtained at 13:00 pm after fluctuating throughout the experimental period. The Figure indicates a closely related patterns between the T_p and T_c which increases with increase in time.

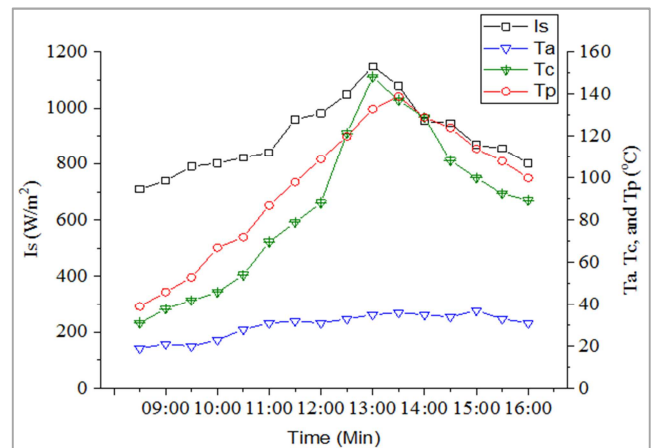


Figure 9. Plot of Ambient temperature, Temperature of the concentrator, solar radiation, temperature of the observer plate against time.

3.2. Load Test

Initial experiment was conducted for a load of 500g of water in the solar concentrator was investigated and the temperature values obtained during the experiment was recorded and presented in the figures.

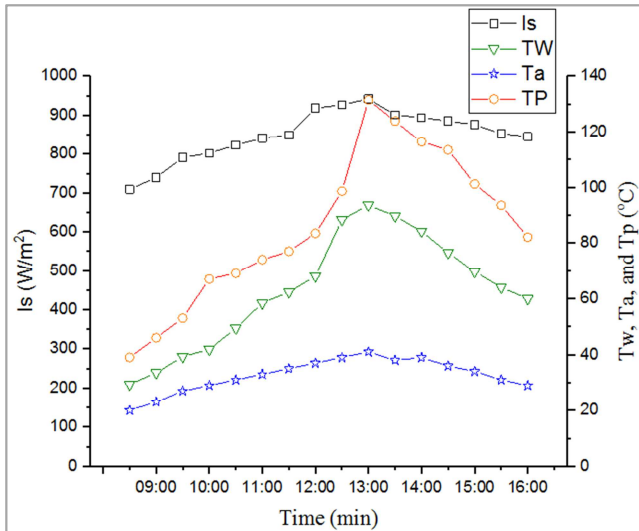


Figure 10. Variation of solar radiation, Temperature of water, ambient temperature, and absorber plate temperature.

Figure 10 presents the variation of solar insolation, temperature of the boiled water, ambient temperature, and temperature of the absorber plate. The parameters shows similar trend where the values increases with time until a peak value was attained at 13:00 pm and then decreases toward the late hours of the day as the sun intensity decreases. It can be seen from the figure that the water attained a maximum temperature of 93.62°C at 13:00pm. The peak temperature of the absorber plate is 131.5°C and the ambient temperature of 41°C was obtained at 13:00 hrs at the same time, the solar radiation was found to be 942 w/m² when the sun is directly overhead.

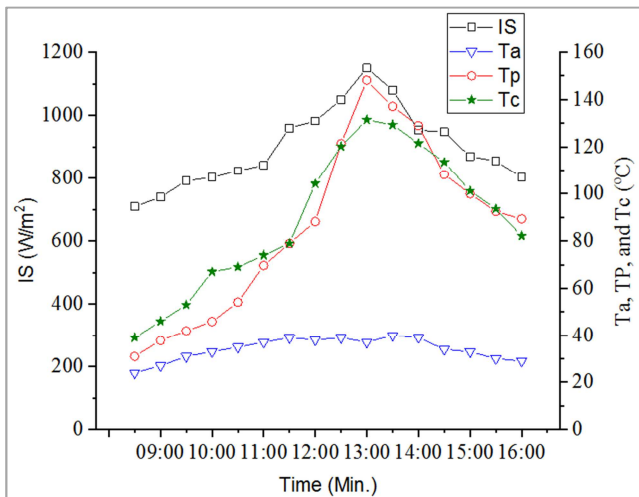


Figure 11. Variation of solar radiation, ambient temperature, temperature of the absorber plate and temperature of the concentrator for cooking rice.

Figure 11 shows the variation of the solar insolation, the ambient temperature, temperature of water and the temperature of the absorber plate for cooking of 3 kg of rice. It can be seen from the plot that the temperatures varies with time of the day. All the temperatures increases with time until a peak value is attained. This peak values was attained at 13:00

hrs. where the sun is directly overhead. It can be seen from the figure that the solar radiation reaches a peak value of 1170 W/m², while the absorber plate attained a peak value of 134.3°C at this time the rice is already fully cooked. The ambient temperatures has a peak value of 37°C at that particular point in time.

Figure 12 presents the variation of solar insolation, ambient temperature, temperature of the concentrator and temperature of the absorber plate. For cooking 2kg of yam The figures shows similar trend where the parameters increases gradually until a peak value is attained. The maximum solar insolation is 1200 W/m² at 13:00 hrs. The peak ambient temperature is 40°C while the temperature of the concentrator has increased up to 142°C, and the temperature of the absorber plate rose up to 131°C. The water started attaining the boiling point 3 hrs after the commencement of the experiment i.e. 11:30 and the yam got cooked 1:30 minutes after placing inside the absorber plate.

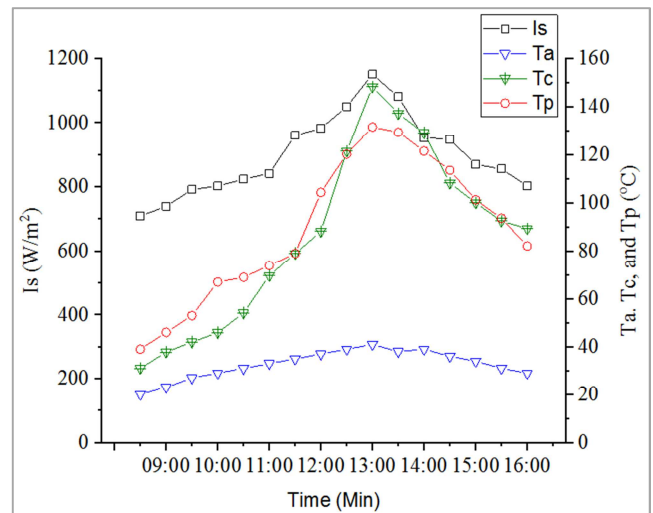


Figure 12. Variation of solar radiation, ambient temperature, Temperature of the concentrator, and temperature of the plate.

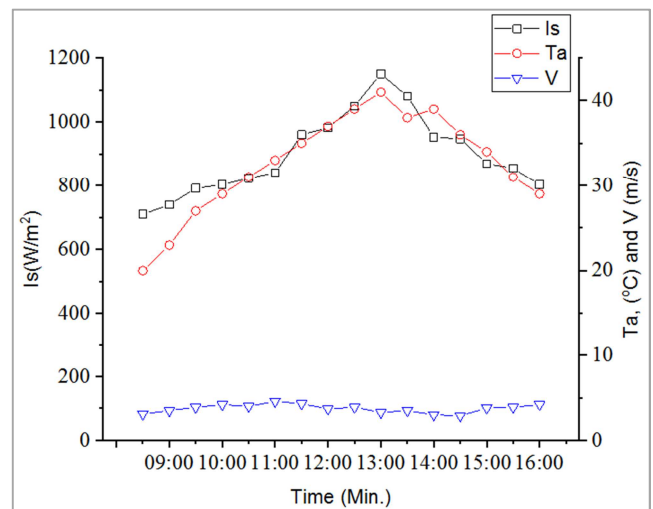


Figure 13. Variation of Ambient Temperature, Wind speed against Time.

Figure 13 presents the variation of solar radiation (Is),

ambient temperature (T_a), and wind speed (V). From the figure it can be deduce that both the I_s and T_a follow similar trend where the values increases gradually with time from the early hours of the day until a peak value is attained at 13:00 hrs before it later decreases with increase in time. However, the wind speed fluctuate throughout the day where it increases and decreases as the time run by. The figure indicates that the solar radiation and the ambient temperature attained the peak values of 1015 W/m^2 and 41°C at 13:00 pm while the wind speed at that point in time is 3.3 m/s , however the peak wind speed is 4.6 m/s at 11:00 am.

3.3. Discussion

3.3.1. Performance Evaluation

To assess the concentrator's performance, a series of experiments were conducted under various environmental conditions. The collected data includes energy output, efficiency, and cooking/heating times. A comparison is made between the hybrid concentrator and traditional solar concentrators to highlight the advantages of the proposed design.

3.3.2. Performance Indicators

The developed solar concentrator was tested to investigate the thermal performance as well as the economic feasibility for cooking and heating. The thermal performance tests were carried out in the form of first figure of merit (no load) (F_1) as per the standard (IS 13429 (part 3):2000. The ambient temperature, solar irradiance water temperature and temperature of the concentrator, and the absorber plate temperature were recorded to evaluate the performance of the system. The average test was calculated. Figure of merit was used to determine the performance of the solar concentrator. The first figure of merit (F_1) is for the stagnation test (no load) of the solar concentration to be able to assess the maximum temperature attained and temperature profile inside the concentrator. The first figure of merit which is the ratio of the optical efficiency F_{η_0} to the overall heat loss coefficient F_{ul} .

To determine the first figure of merit for the solar concentrator without load, the average data for the solar radiation, ambient temperature and the temperature of the absorber plate was used. Using equation 6 the first figure of merit (F_1) is calculated to be $0.64214^\circ\text{C m}^{-2} \text{ W}^{-1}$, at stagnation plate temperature of 88°C , ambient temperature of 29.9°C , and solar radiation of 904.7 W m^{-2} respectively. Using equation 8 the overall utilization efficiency of the hybrid solar concentrator is calculated to be 26.3% , and the cooking power is calculated to be 177.912 . The findings from this study has demonstrated a significant improvement when compared to works of Gwani, et al. [18] whose solar oven produces a highest temperature of 133°C . and Yahuza et al., [19] whose highest temperature of 104°C .

4. Conclusion

In this study, hybrid parabolic dish solar concentrator has been designed and tested in an experiment. The design system

is a viable alternative source of energy cooking and heating of water especially in the rural health care centers. Findings from the study revealed that the performance of the hybrid parabolic dish solar concentrator improved greatly with the presence of the reflectors, and both cooking and heating of water can be achieved simultaneously with the hybrid parabolic dish concentrator. Moreover high temperature values, better efficiency, and reduced cooking time could be attained by the hybrid parabolic dish concentrator. The analysis confirms the figure of merit is a reliable performance rating criteria for the hybrid parabolic dish solar concentrator. The performance will bring the parabolic dish concentrator close to being accepted as a realistic alternative method of cooking and heating, and it has the potential to cut down fuel wood usage, encourage afforestation and improve the quality of life of the women or people in the rural. However, further work can be done to improve the performance of the parabolic dish solar concentrator.

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Acknowledgments

The Authors would like to appreciate the Tertiary Education Trust Fund for the institutional based Research (IBR) Grant provided to carry out this research, and Kebbi State University of Science and Technology for providing the conducive environment to carry out the research.

Conflicts of Interest

The authors declare no conflicts of interest.

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