



DETERMINATION OF THERMAL EFFICIENCY AND COOKING POWER OF PARABOLIC SOLAR CONCENTRATING SYSTEM WITH THERMAL COMPENSATOR FOR DOMESTIC APPLICATIONS

*^{1,2}BANDE A. B.; ²GARBA M. M.; ²ALIYU S., ²HAMZA B.S. and ³SHEHU A.

¹Department of Physics, Shehu Shagari College of Education, Sokoto, Nigeria

²Department of Physics, Usmanu Danfodiyo University Sokoto, Nigeria

³Department of Physics, Shehu Shagari College of Education Sokoto, Nigeria

ABSTRACT

Energy and the environment have a strong relationship. The production and consumption of energy is one of the biggest causes of environmental damage on earth. Therefore, the rapid increase in the level of CO₂ and other greenhouse gases are given out during burning fossil fuel rise or unsteady of fuel prices are the main purposes led to a search to more effectively utilize a different sources of renewable energy. To reduce the consequences of greenhouse gases emitted by burning fuel for energy, which course depletion of the ozone layer and global warming. Therefore, the use of solar radiation directly as a source of energy has proved in the past to be less economical and affordable. The paper was aimed at determination of the performance of a parabolic solar concentrating system with a thermal compensator for domestic applications using thermal efficiency and cooking power. The parabolic dish solar collector (PDSC) with a focal point of 6.15 m, aperture area of 5.8 m² and rim angle (ϕ°) of 45^o was designed and constructed for the determination of the variables. The PDSC was made of stainless steel reflector sheet in such a way that both the manufacturing and assembly method do not require complicated skilled techniques and cost. Since the PDSC is for high temperature steam generation, hot water and cooking application. A finite element stress test analysis was conducted to determine the thermal efficiency and cooking power of the system under various weather conditions. A simple manual solar tracking mechanism was employed, and the results of the system performance were also reported. The efficiency according to the finding depends on the optical properties of the materials involved, the geometry of the collector, and the various imperfections arising from the construction of the collector. The thermal efficiency and cooking power of the system were determined and obtained to be 54.4% and 543.1W respectively.

Keywords: thermal efficiency, stainless steel parabolic reflector, thermal compensator, cooking power and steam generation.

INTRODUCTION

The global energy crisis is one of the major critical issues facing the world and sustainable environment with the depletion of charcoal, coal, oil and natural gas and the increasing of energy demand. Energy demands in the world have been continuously increasing recently due to growth in population and industrialization. It

is obvious that the conventional energy sources obtained from fossil Fuels are under increasing demand and there is a need to search for alternative sources to complement these energy sources (Sadik *et al.*, 2013). Parabolic solar dish concentrators are used to achieve high thermal energy and this concentration of sunlight in form of solar radiation is achieved by reflecting or refracting the incident flux on the aperture

area (reflecting surface of the concentrator) onto a smaller absorber area (receiver) (Flavia *et al.*, 2016).

The low cost parabolic solar collector was designed for medium thermal applications, the system was made off with a spiral coil absorber for calculating its optical performance, and a mathematical and physical model of the new offset type parabolic concentrator system was presented. (Pavlović *et al.*, 2016). A static solar concentrating collector called 3D was developed that can be used as low cost technology with the aim of production of portable hot water in rural area of India. The ray tracing software for evaluation of the system was used and optimization of the concentrator profile and geometry is carried out to improve the overall performance of the system designed Saleh (2013).

The satellite dishes of 2.405m diameter with an aluminum frames as a reflector to reduce the weight of the structure and the cost of the concentrating solar system.in the designed reported by (Kaushika and Reddy, 2000), the average temperature recorded for the system was 300 °C , when the receiver absorber was placed at the focal point. An experimental investigation of a solar parabolic dish collector with aperture area of 20m², with the aim to study its performance with the modified cavity receiver was presented, and the average value of the overall heat loss coefficient for the system was found to be about 356 W/m² (Reddy *et al.*, (2013). Direct steam generation achieving 90% thermal efficiency at 535°C with a parabolic dish and cavity type receiver has been reported based on experimental results using a 500 m² dish (Lovegrove *et al.*, 2011). The research would try to find out a more efficient and convenient method of harnessing the available solar radiation using parabolic solar concentrator for thermal

steam generation and encourage the use of friendly technology for domestic and industrial use.

MATERIALS AND METHODS

Construction Materials

The parabolic dish concentrating system was constructed using locally available and affordable materials, and the specification of the materials used is shown in Table 1. In the selection of materials for the construction, the following were highly considered; local availability, low cost, easy handling during fabrication, lightness of weight for easy handling during use, ability to withstand environmental and operating conditions and non-toxic effects.

A detailed list of the materials, their specifications and quantities used for the construction of the parabolic dish collector are shown in Table 1.

Table 1: Specifications and Quantity of Materials Used for Construction of the Concentrator

Material	Specification	Quantity
Stainless steel reflector type	10.0m	6
Copper pipe tube	0.40m	4
Connecting arms	0.35m	4
Cross bar	0.81m	1
Adjuster	0.30m by 0.23m	1
Receiver sitter	0.51m	1
Receiver adjuster	0.43m	1

Experimental Setup and instruments used

The water boiling test experiments for steam generation were performed and the maximum temperature attained by the parabolic concentrating system was measured by using a mercury in glass thermometer and recorded, the cooking

power and thermal efficiency of the systems were also evaluated. The instruments used during instrumentation, include the following listed in Table 2.

Table 2: List of Instruments used in the Measurement

Parameter Measured	Instrument Used
Solar insolation	Pyranometer
Wind speed	Anemometer
	Maximum and minimum mercury in glass thermometer
Content temperature	Digital thermocouple data logger
Ambient temperature	Digital thermocouple data logger
Weight of water and other food substance	Electronic Weighing balance

Optical Design of the Solar Parabolic Thermal Concentrator

The optical design of the system was done based on the geometry of the dish concentrator. The parabola shape reflector is the meeting point in which distances from a fixed line and a fixed point are equal. Figure 1, shows a parabola, where the fixed line is called the directrix and the fixed-point F , and the focus. The line perpendicular to the directrix and passing through the focus F is called the axis of the parabola. The parabola intersects its axis at a point V called the vertex, which is exactly midway between the focus and the directrix (Fareed *et al.*, 2012).

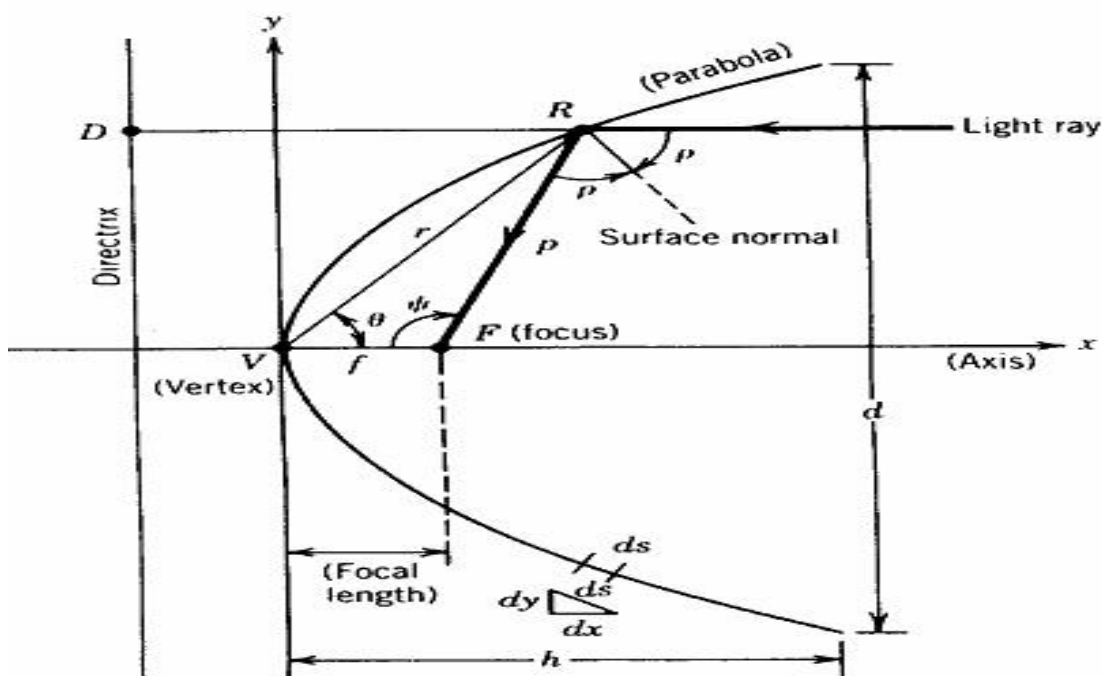


Figure 1: The parabola intersects its axis at a vertex, (Pavlovic *et al.*, 2016).

A mathematical equation for the parabola shape in Cartesian and cylindrical coordinate systems was employed (Pavlovic *et al.*, 2016),

$$x^2 + y^2 = 4fz \quad \& \quad z = \frac{r^2}{4f} \tag{1}$$

Where x and y are coordinates in the aperture plane and z is the distance from the

vertex measured along the line parallel with the paraboloid axis of symmetry; f is the

DOI: 10.56892/bima.v6i03.66

focal length of the paraboloid i.e. distance from the vertex to the focus along the paraboloid axis of symmetry. The relationship between the focal length and the diameter of parabolic dish is called relative aperture and it defines the shape of the paraboloid and the position of the focal point.

Design Description of Solar Parabolic Concentrator

The parabolic dish solar collector or concentrator comes in twelve parts or pieces like curvilinear trapezoidal petals-shaped reflector and is assembled using bolts and

nuts to tighten the parts together as shown in Figure 2, 3 and 4. Each part of trapezoidal petals-shaped reflector was made up of light steel materials, the upper surface was then fixed with stainless steel reflector sheet in order to have a high efficiency of reflecting the solar energy onto the receiver. Therefore, the components were assembled into the parabolic dish concentrating system for experimental setup with a receiver placed at the focal point for collection of reflected solar radiation from concentrating solar collector with a thermal compensator as shown in figure 5.



Figure 2: Assembled of trapezoidal petal shaped reflector of parabolic dish concentrator.

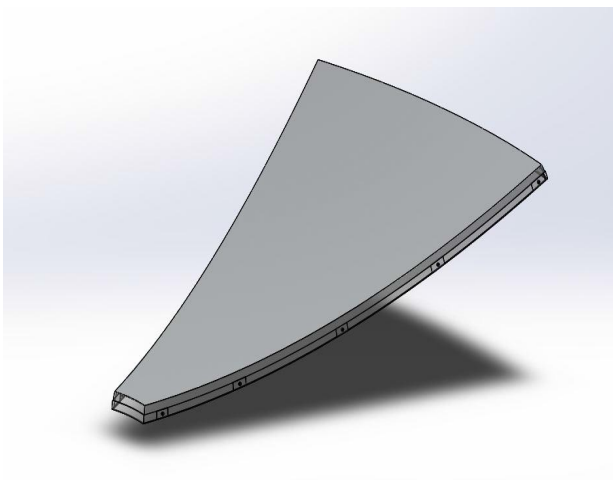


Figure 3: Trapezoidal reflective petal of solar parabolic concentrator.



Figure 4: Constructed parabolic dish solar concentrating collector.



- Thermal compensator
- Control valve
- Reciever -absorber
- Copper tube pipe
- Outlet tube
- Parabolic solar collector

Figure 5: Experimental setup of parabolic dish concentrating system with thermal compensator.

Determination of the Focal point of the parabolic concentrator

In determining the focal point of the dish, the mathematical method which entails using the parabola equation to calculate the required parameter adopted as shown in figure 6. Therefore, equation (2) was used for the determination of the focal point.

$$f = \frac{D^2}{4d} \quad (2)$$

Where D is the longest width and d is the depth of the parabola

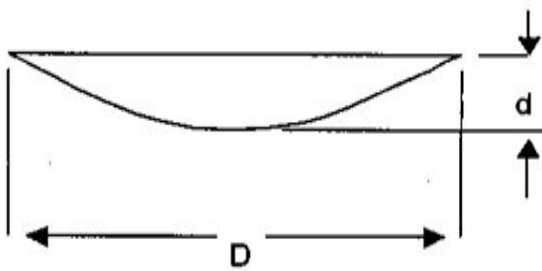


Figure 6: Schematic diagram for Determining the Focal Point (NOVA, 2007).

Determination of Concentration Ratio of the Concentrating Solar Collector

The energy utilization based on the thermal energy parameters and optical efficiency of the system considered and the concentration ratio of the collector was determined using equation (3) (Eltahir, 2013). The geometrical concentration ratio is defined as the collector aperture area A_a , divided by the surface area of the receiver A_r (Eltahir, 2013).

$$C_g = \frac{A_a}{A_r} \quad (3)$$

Determination of Thermal Efficiency of Concentrating Solar Collector

The efficiency is defined as the ratio of the thermal power absorbed by the heat transfer fluid to the direct normal irradiance on the aperture area (Najla *et al.*, 2011), Therefore, the thermal efficiency was determined using equation (4)

$$\eta_{th} = \frac{(T_{wf} - T_{wi})M_w C_w}{I_b A_c} \times 100\% \quad (4)$$

Where, η_{th} Thermal efficiency in %, T_{wf} Final temperature of water measured in $^{\circ}\text{C}$, T_{wi} Initial temperature of water measured in $^{\circ}\text{C}$, M_w Mass of water measured in kg, C_w Specific heat capacity of water 4200J/Kg/K (Constant) and A_c Aperture area of the collector measured in m^2

It was 0.75kg of water was boiled in 5 minutes at solar radiation of 969W/ m^2 and

wind speed of 0.47m/s. using pot like receiver as a cooking utensil of 70.66 m^3 , containing 1000 cm^3 of water.

The magnitude of the efficiency of the system by 01:00pm was calculated to be $\eta_{th} = 54.4\%$ Therefore, the values obtained for the thermal efficiency is line with the 56% obtained by Ibrahim (2012), and lower than the 60% obtained by Eswaramoorthy and Shanmugam (2012),

Determination of Cooking Power of the Parabolic Dish Concentrator

The cooking power, P , is defined as the rate of useful energy available during the heating period. It may be determined as a product of the change in water temperature for each interval and mass and specific heat capacity of water contained in the cooking utensil. Dividing the product by the time contained in a periodic interval yield the cooking power in Watts.

The cooking power of the parabolic dish solar collector was calculated using equation (5), given by (Funk, 2000) thus:

$$P = M_w C_w \frac{(T_{wb} - T_{wa})}{\tau} \quad (5)$$

$$P = 543.1W$$

Where, M_w is the mass of the cooking utensil or boiling utensil, C_w is the specific heat capacity of water, T_{wb} is the final temperature of the water, T_{wa} is the initial temperature of the water, τ is the time taken for the water to boil, I_b is the intensity of direct solar irradiance on the parabolic concentrator.

RESULTS

Water Boiling Test

The result of the water boiling test is shown in Figure 7. The system shows that the

highest temperature recorded is that of the parabolic concentrating system; the corresponding global solar radiation and wind speed were 98.7°C, 948W/m² and 0.70m/s respectively at 13:00 pm on the day of experimentation. The result clearly shows the effect of the atmospheric parameters on the water temperature. It was clearly noticed that the weather was fluctuating due to the cloudy sky which tends to slow down the boiling process. The atmospheric temperature was in constant fluctuation between 75.3°C to 83.5°C between the hours of 11:30 am to 12:30 pm with the highest ambient temperature reached at that same time. The maximum intensity of solar radiation was found between 12:00 pm to 1:00 pm.

Steam Test

The steam generation test was conducted on the second day which was having clear weather. Figure 8, shows the representation of the data in an excel graph. The atmospheric parameters were in favor of the rise in temperature with the highest temperature being attained very fast even before noon, while the atmospheric temperature was favorable. The highest solar insolation reached and recorded in this clear weather was 884W/m². The graph of result in figure 8 shows that, temperature was directly resonating with the fluctuating intensity of solar radiation between the hours of 14:00pm to 14:30pm.

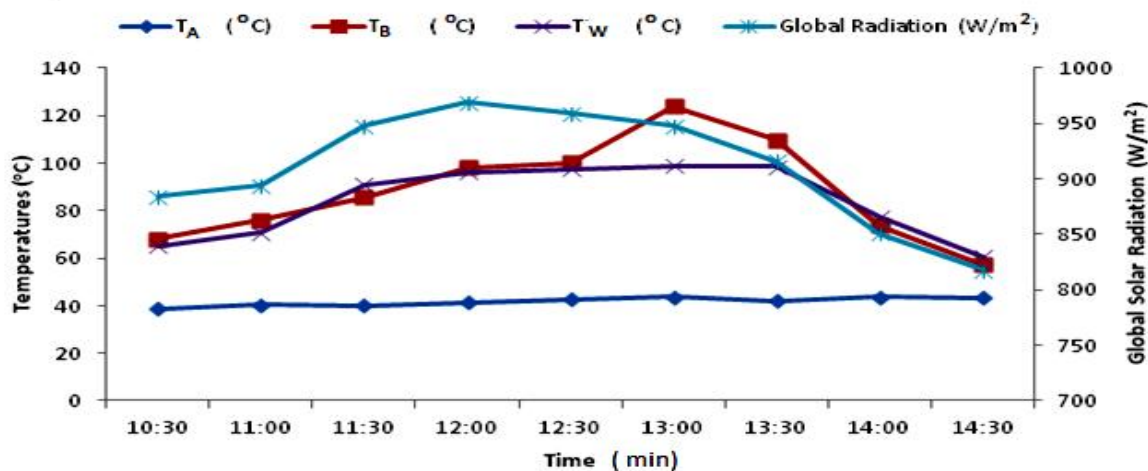


Figure 7: Results of temperature variation with time and corresponding global solar radiation of water boiling test.

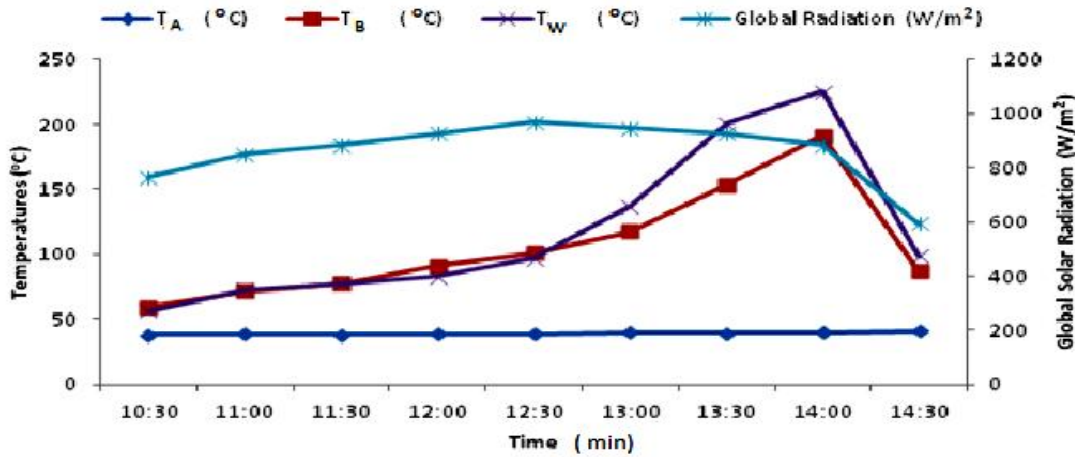


Figure 8: Results of temperature variation with time and corresponding global solar radiation of steam generation test.

Cooking Test

The Cooking test result was conducted on the third day which was a little bit cloudy day that covered the intensity of solar radiation and others weather parameters for the effectiveness of the system compared to the result obtained in steam generation test. Figure 9, shows the results of the rice

cooking test, which clearly shows the dependence of the cooking test on the atmospheric parameters with the temperature falling between 11:30 am to 1: 00 pm. The time taken for the rice to be well cooked was a little bit longer, obviously due to the rapid in temperature fall as a result of the cloud covering the intensity of solar radiation (uncontrolled factor) (Funk, 2000).

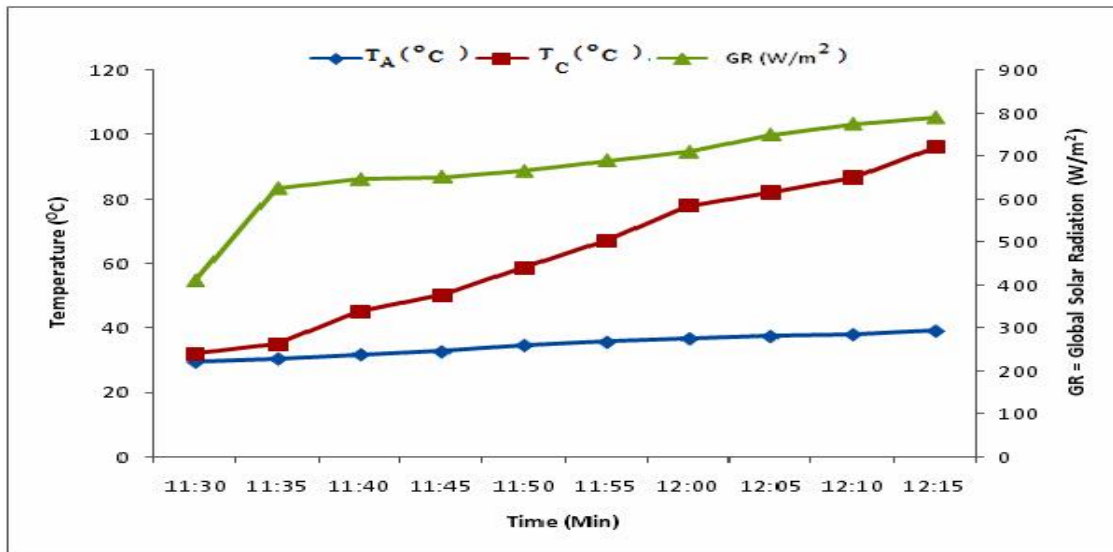


Figure 9: Results of temperature variation with time and corresponding global solar radiation of cooking test.

DISCUSSION

The experimental results obtained for the boiling test was depicted in Figure 7. The Figure shows that, the temperature of water obtained by the system was continuously increasing to reach a temperature value of 100°C as the ambient temperature continuously increased to a certain value of 43°C and a corresponding increase in wind speed. By 13:00 pm the temperature value of the system gradually decreased to a certain value, this could be due to the gradual decrease of the intensity of solar radiation and ambient temperature as the result of cloud covered; Therefore, it is uncontrolled parameters or factors, similar results were reported by (Funk 2000) and (Serah 2014). Therefore, the maximum temperature required for water to boil was achieved, and a significant limestone was achieved compared to the temperature of 90°C obtained by (Asere *et al.*, 2003), and the temperature value is similar to 100°C obtained by (Ibrahim, 2012).

Similarly, Figure 8 shows that the highest temperature recorded of the solar concentrating system during the steam generation test, corresponding global solar radiation and wind speed were 225.3°C, 884W/m² and 0.40m/s respectively at 14:00 pm on the second day of experimentation. On that day the atmospheric condition or weather was cleared around 12:30 – 14:00 pm. Therefore, the atmospheric parameters were in favor of the rise in temperature with the highest temperature being attained very fast even before noon, the highest solar radiation reached and recorded in this clear weather was 884w/m²., similar results was reported by (Funk, 2000). The temperature

value is lower than 300°C obtained by (Kashika and Reddy, 2000).

Figure 9 shows that, the results of temperature variation with time and corresponding global solar radiation. The result revealed that, the highest temperature recorded for cooking test, the corresponding global solar radiation and wind speed were recorded 96.4°C, 790W/m² and 0.47m /s respectively. The result clearly shows the dependence of the cooking test on the atmospheric parameters with the temperature falling down between 11:30am to 1:00pm. The time taken for the rice to be well cooked was a little bit longer, obviously due to the rapid in temperature fall as a result of the cloud covered the intensity of solar radiation (uncontrolled factor) according to (Funk, 2000). The temperature of cooking material (rice) increased continuously as the ambient temperature and corresponding global solar radiation increased, while the wind speed decreased gradually. The increase of wind speed from 11:30pm to 1:00pm did not affect the increase of temperature of the cooking material, as the global solar radiation and ambient temperature were increasing. The temperature result obtained during cooking test was in lower value compared to the temperature obtained in steam and boiling test and this could be as a result of observable delay in response to the solar fluctuations., similar results was reported by (Funk, 2000). Therefore, the temperature obtained is line with 95°C by (Gang *et al.*, 2012),

CONCLUSION

The parabolic concentrating solar collector with thermal compensator was found to be able to produced boiling water and steam with a temperature as high as 100°C and

225.3°C respectively, the system can be used for some domestic applications. The thermal efficiency and cooking power were found to be 54.4%, and 543.1W respectively. The variation of temperature results obtained on some days during experimentation could be a result of both optical and thermal losses from the reflector and receiver (cooking utensil). Furthermore, the results of the tests conducted were hindered by the fluctuation of the atmospheric parameters as a result of the cloud and solar fluctuations which is one of the uncontrolled atmospheric parameter and as well as inefficiency caused by manual tracking system or mechanism. But it can be said that significant limestone was achieved.

REFERENCES

- Asere, A.A., Habou, D. and Sambo, A.S. (2003). Performance of a compound parabolic solar cooker. *NJERD*, 2(1): 30-37.
- Burgess, G., Lovegrove, K., Mackie, S., Zapata, J. and Pye, J. (2011). Direct Steam Generation Using the SG4 500 m² Paraboloidal Dish Concentrator", Presented at 17th *Solar PACES Conference, Granada, Spain, pp. 15-18*.
- Brenton, G and Anjaneyulu K. (2007). Tri-generation concentrating solar power system for rural applications. Technical Report ES2007-36169, *Sustainable Energy Science and Engineering Center*, 4: 1387-1393.
- Eltahir Ahmed Mohammed (2013). Design and testing of a solar parabolic concentrating collector. *International conference on renewable energy and power quality ISSN 2`72-038X, NO.11*.
- Eswaramoorthy, M. and Shanmugam, S.(2012). The Thermal Performance of a Low Cost Solar Parabolic Dish Collector for Process Heat, Energy Sources: *Recovery, Utilization, and Environmental Effects: 34: 1731-1736*.
- Fareed, M.M., Auatf, S., Yaseen, H., Mahmood, Mohamad, A.K. Ahmaed. (2012). Design and study of portable solar dish concentrator. *International journal of Recent Research and Review*. 3: 2277-8322.
- Flavia, V.B., Joao, L.A., Filipe, B.R. and Jose, C.F.T. (2016). Development of solar concentrator with tracking system. *Journal of mechanical science*. 233-245.
- Funk, P.A. (2000) Evaluating the international standard procedure for testing solar cookers and reporting performance. *Solar Energy*. 68(1), 1-7.
- Gang, P., Guiqiang, L., Xi, Z., Jie, J. and Yuehong, S. (2012). Experimental study and energetic analysis of a compound parabolic collector (CPC) type solar water heater system using higher temperature circulation in water. *Solar Energy* 86: 1280 – 1286.
- Kaushika, N.D. and Reddy, K.S. (2000). Performance of low cost solar paraboloidal dish steam generating, *Energy Conversion & Management* 41: 713- 726.
- Kothari, D.P., Singal, K.C. and Rakesh, R. (2012): Renewable Energy source and Emerging Technologies. Second edition. 133-146.
- Najla, G., Halima, D., Sofiane, B. and Noueddine, S. (2011). A comparative study between parabolic trough collector and linear Fresnel reflectors technology. *Energy precedia*. 6: 565-572.
- Lovegrove, K. Burgess G. and Pye, J.(2011). A new 500 m² paraboloidal dish solar concentrator', *Solar Energy* 85: 620-626.
- NOVA-(2007). Finding the Focal point,



DOI: 10.56892/bima.v6i03.66

- Saved by the Sun//Student handout, WGBH, Educational Foundation.
- Pavlovic, S., Vasiljevic, D. and Stefanovic, V. (2014). Optical design of a solar parabolic thermal concentrator based on trapezoidal reflective petals, *Proceedings, International Conference on Advances Technology & Sciences. 1166 – 1171.*
- Pavlovic, S.R., Evangelos, A.B., Velimir, P.S., Christos, T. and Zoran, M.S. (2016). Design, simulation and optimization of a solar dish collector with spiral coil thermal absorber. *Thermal science. 4: 1387-1393.*
- Reddy, S. V., Kaushik, S.C., Ranjan, K.R. and Tyagi, S.K. (2013). State-of-the-art of solar thermal power plants—A review. *Renewable Sustainable Energy Rev 27: 258–273.*
- Roldan, M.I.S., (2017). Concentrating solar thermal technologies. *Green energy technology 3: 319-458.*
- Sadik, U., Mohammed, U.K., Garba, M.M., Yahaya, H.N., and Ali, A.U. (2013) Experimental performance evaluation of parabolic trough concentration. *International Journal of Environmental and Bioenergy, 8(2), 86-93.*
- Saleh A.(2013). An Optical Analysis of a Static 3-D Solar Concentrator, *Solar Energy, 88: 57-70.*