Nigerian Journal of Solar Energy, Vol. 25, 2014.

Mitigation of Climate Change by Development of Hemispherical Solar Concentrator for Solar Energy Generator using Thermocouple Technique

[1*]Babarinde, B.T., [2]Akoshile, C.O. and [2]Nwankwo, L.I.
[1]Department of Physics, Kwara State College of Education, Ilorin, Nigeria.
[2]Department of Physics, University of Ilorin, Ilorin, Nigeria.

Abstract - *This study involves the development of hemispherical solar concentrator for solar to electrical energy conversion using thermocouple method as a means of mitigating impacts of climatic change occurring through the use of fossil fuel. The paper-made hemispherical solar concentrator of radius 0.255m was lined with 252 square plane mirror pieces each of area 0.0016m^2 and arranged side by side producing a total focusing area of 0.4032m^2. A copper cup absorber of length 0.10m, radius 0.075m and absorbing area 0.00442m^2 was utilized as the solar to thermal absorber producing high temperature for the hot junction of the copper - constantan wires used as thermocouple and resulting in the generation of electricity. The magnitude of the electromotive force produced between the hot and cold thermocouple - junctions was found to depend on the magnitude of the temperature difference between the hot junction where the focus of sun radiation by the concentrator produced the very high temperature needed and the cold melting ice temperature. Enhanced absorption was obtained using black coating on the absorber surface area where the solar radiation falls. The concentration ratio realized exceeded 91. The emf response with one thermocouple had its maximum value of 4.2 mV at noon. It is therefore anticipated that the employment of such solar to electrical energy conversion technique will reduce dependence on fossil fuel as a precursor to environmental pollution control.*

Keywords - climate change mitigation, solar energy, concentrator, thermocouple, electricity

1. INTRODUCTION

As human civilization has advanced over the decades, the need for more energy has greatly increased. At present, the world has a substantial reliance on energy originating from fossil fuels, such as coal, petroleum and gas due to the high energy yield of these resources for relatively low cost. Although there exists an economic incentive to continue using oil; the process of extracting energy from fossil fuels generates greenhouse gases, which has been shown to lead to adverse effects on air quality, ocean acidity, and global climate change (Abdulrahim et al., 2010), and other authors. Unfortunately, relative comparison of cost estimates between the use of petroleum and solar energy resources in the United States of America, in 2011 shows a contrast of \$0.04 per KWh for petroleum as against \$0.24 KWh for solar systems (Abdulrahim et al., 2010). Renewable energy generation has not been sufficiently integrated into the Nigerian energy infrastructure. The accompany environmental degradation and its consequential cost could in the long run push what looks like financial gain in using fossil fuel instead of environmentally friendly renewable energy, to be financial loss beside the attendant negative health impact, irreplaceable loss of life and damaged environment that may result from climatic borne disasters.

Nigeria is blessed with abundant solar energy resource (Babatunde et al., 1990) having an annual average daily solar insolation of 5.25 KWh/m^2 per day varying between 3.5KWh/m^2 at the coastal areas and 7.0 KWh/m^2 at the northern boundary and an average daily sunshine of up to 11 hours (Ebunilo et al., 2013). This huge solar energy reservoir which is capable of meeting the electricity demand of the nation is yet left untapped (Kadiri et al., 2011). The amount of energy generated by a nation is critical to the nation's economic growth and development. Presently, Nigeria generates about 2000MW-4000MW of electricity for the use of a population of about 170 million people, which is considered absolutely inadequate (Aliu et al., 2013).

The aim of this study is to develop a solar concentrator-absorber system to convert the electromagnetic radiation from the sun, first to thermal energy and finally to electrical energy by employing the thermocouple technique and using locally sourced materials at much reduced cost. The main focus of the study therefore, is to introduce and initiate a heat production source accompanied by electricity generation process from heat devoid of greenhouse gases that could result in global warming which alters the climate. The heat and electricity generated from the system could be

*Corresponding author Tel: +234-8131083700
Email: babarindet8@gmail.com

utilized for diverse domestic applications at low cost and in urban and rural areas.

Akoshile, (2005) reported the technique of converting solar to electrical energy using thermopile technique. The work was however carried out at low temperatures. Since the technique has gone on to show that heat required can be harnessed from solar energy, and that there is a direct relationship between temperature difference existing between junctions and electromotive force (hence current) produced, what should then be focused on as aim is to demonstrate this process at higher temperatures. Higher temperatures can be obtained from solar energy source by using concentrator technique and this is what this study was out to demonstrate.

2. MATERIALS AND METHODS

2.1 Description of Prototype

The solar concentrator is made of paper-mould with equal size of square plane mirrors forming its inner lining with little or no gaps between the mirrors. The concentrator approximates a large concave mirror with the principal focus located at the point where all the parallel rays coming from the distant sun are converged after reflection. The receiver or absorber is a copper cup, suspended directly at the focal point of the concentrator and filled with a working fluid. The high intensity radiation collected by the circular base of the absorber yields an equally high temperature at the point. Insulation of the absorber, to reduce heat losses, was done by filling the outer surroundings with sawdust. Two dissimilar wires connected end to end constitute a thermocouple. One end is inserted into working fluid inside the absorber near the focal point forming the hot junction while the other end is inserted into melting ice, called the cold junction

.

2.2 General Design Considerations

The nature, availability, durability and practical usability of materials are important factors in the construction of a concentrator. The materials to be used must be suitable for moulding, bending and eventual stiffening for shape retention. Cost and resistance to high winds, rain and storm conditions are also necessary considerations.

- The solar concentrator is made of paper-mould with equal size of square plane mirrors forming the inner lining with little or no gaps between the mirrors.
- Mirrors were cut to desired size and shape to be mounted on the concentrator.
- Concentrator approximates a large concave mirror with the principal focus located at the point where all the parallel rays coming from the distant sun are converged after reflection.
- The receiver or absorber is a copper cup, suspended directly at the focal point of the concentrator and filled with a working fluid.
- Working fluid used for the study was molten salt. The high intensity radiation collected by the circular base of the absorber yields high temperature at the point.
- Insulation of the absorber was made to reduce heat loss. This was done by filling the outer surrounding of the cup with sawdust.
- Thermal to electrical energy conversion was done using two dissimilar wires connected end to end to constitute a thermocouple. One end was soldered to the absorber that is positioned at the focal point forming the hot junction while the other end was inserted into melting ice, called the cold junction.

2.2.1 The Hemispherical Solar Concentrator

Solar concentrators can take several shapes, conical, parabolic, spherical, and many more depending on the application for which each is meant. In this study, hemispherical concentrator was selected because it is geometrically more convenient to prepare a spherical shape and slice it into two than prepare other shapes. Moreover, the analytical method of determining the focus is well known and can be handled with ease. Hence, the focus could be predicted with much accuracy. The hemispherical structure was cast from paper. Old newspapers were soaked inside water and left for days. When it has been considered softened enough, they were pounded inside a mortar until turned into a pasty substance. Starch was added to the moist paste as binder to increase the cohesive forces and give additional compactness. The paste was then moulded to a thickness of 4 cm round the back of a big hemispherical-shaped clay pot turned upside-down. Clay pot could not be used because it is heavy and is easily breakable. The whole assembly was then left under the sun to dry for a number of days. When it is considered to have dried enough, the cast was removed from the back of the pot resulting in a semi-spherical mould (Fig. 1).

The dimensions of the mould were as follows:

Diameter of the upper circle (D) = 0.51m
Depth of the hemisphere (H) = 0.252m
Semi-circumference of curved surface (C) = 0.86m

Using the sub-spherical surface area equation $A = \frac{1}{2}(4\pi R^2)$, the total inner surface area of the mould was calculated and obtained as $0.409m^2$.

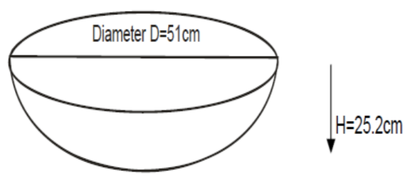

Fig. 1: Hemispherical Paper Mould

2.2.2 Mirrors

A large slab of plane mirror was cut into squares of side L (0.04m x 0.04m) equal to an area of 0.0016 m^2. A total of 252 mirror pieces were used giving a total mirror reflecting surface area of 0.4032 m^2. This area agrees with the calculated surface area of the paper mould used. They differ by about 0.006 m^2 which is less than 2% which could be attributed to gaps created in fixing the mirror bits. Prior to attaching the mirrors, thick strong paper was cut into dimensions 4 cm x 4 cm to which short flexible wires of 10 cm length was firmly glued to the back of each of the square mirrors. The attached wires were for maneuvering the mirrors for good focusing position. Also, before arranging the mirrors, a very thick sheet of polythene was used to cover both the inside wall and the back of the spherical paper mould to prevent it from being damaged by rain. The mirrors were arranged side by side forming an inner lining of the paper mould. This was done by using a metal scriber to first puncture the paper mould and then inserting the wire into the hole. The end of the wires emerged at the back of the mould and was bent so that the mirror clings firmly to the mould.

2.2.3 Collector stand

The wooden collector support stand was designed with the East-West horizontal single-axis solar tracking borne in mind. The stand has four wooden arms to hold the hemispherical concentrator. This stand has a joint which can rotate through angles of more than 180^0, and can be hooked facing the sun directly at any time for manual tracking. A wide flat wooden base was provided as part of the collector stand to stabilize it (Fig. 2).

Fig. 2: Collector Stand

2.3 Location of the focal point

The whole arrangement of plane square mirrors could now be regarded as a single large concave mirror and so the focal point was determined using the lens equation

$$\frac{1}{u}+\frac{1}{v}=\frac{2}{R} \qquad (1)$$

where u is object distance, v is image distance and R is radius (half of the diameter) of the concentrator.

Since u = ∞ for parallel and paraxial rays coming from far away sun as object, equation (1) becomes:

$$\frac{1}{\infty}+\frac{1}{v}=\frac{1}{f} \qquad (2)$$

and hence, $$v = f = \frac{R}{2} \qquad (3)$$

With the concentrator fixed on its stand and set facing the sun, a brown coloured paper was moved within the concentrator until a point of convergence of the reflected rays was located. The image located at this focus was nearly circular with the intensity of the sun maximum. The distance between the located point and the centre of the point base of the concentrator was found to be approximately 0.12m which agrees with the calculated value for focal length with less than 5% deviation. Also, the cross-sectional area of the focused rays was about the order of 0.04m by 0.04m; that is equivalent to the area of a piece of the mirror used.

2.4 The Absorber

The absorber shown in figure. 3, is part of the solar radiation collection system. Its function is to collect and retain as much of the concentrated radiation/radiant energy as possible. The concentrated radiation was incident on a carefully selected good absorber of good thermal conductivity and whose surface is painted black to increase its absorptivity. A copper calorimeter cup was chosen as the absorber because it is not corrosive, is malleable and ductile with high melting point and low thermal capacity. The outer circular base of the calorimeter cup served as the receiving surface on which the focused radiation was incident. A copper plate of width 4cm was welded round the cup with a 2cm protrusion beyond the cup and enveloping the receiving surface to further trap radiations that would have been lost by scattering. The dimensions of the copper absorber were

Length of absorber h = 0.10 m;
Diameter of the circular base = 0.075 m and
Absorbing Area (πr^2) = 4.42 x 10^{-3} m^2.

This is comparable with the area of focused radiation (0.0016 m^2). The absorber is therefore a cylinder with one end opened. Hence the surface area of the absorber $(2\pi rh + \pi r^2)$ = 6.77 x $10^{-3}$$m^2$

The concentration ratio (C.R) was found to be = 91.18. This value was obtained from the expression for concentration ratio:

$$\text{C.P.} = \frac{Aperture\ (Concentrator)Area}{Absorber\ Area} \qquad (4)$$

The space between the walls of the two cylinders was filled with sawdust and the mouth capped with wooden cork as insulators to minimize thermal loss by conduction and convection. The copper absorber was encased in an empty large cylinder.

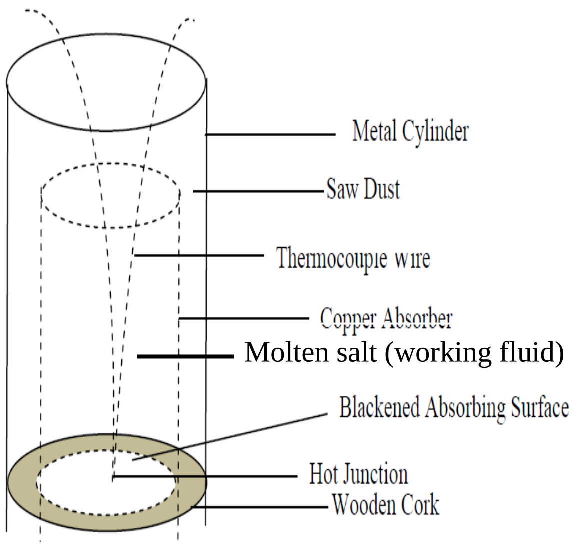

Fig 3. The solar radiation absorber.

2.5 Full Experimental setup

The whole setup comprising the collector stand that holds the concentrator and absorber in position, the thermocouple wires, the melting ice junction and the output-measuring device (which is the multi-meter) is shown in figure 4. A copper/constantan pair of wires was used for the thermocouple. The black-painted surface of the absorber provided the hot junction, while the melting ice served as the cold junction. This provided the needed temperature difference required to generate current due to the emf that developed between the junctions. The active thermocouple is made by placing a junction at the point where the sun ray is focused making a hot junction and an adjacent junction away from the sun as the cold junction. The resulting temperature difference leads to the emf generated which drives current through the couple. Array of these thermocouples could be made to make a thermopile.

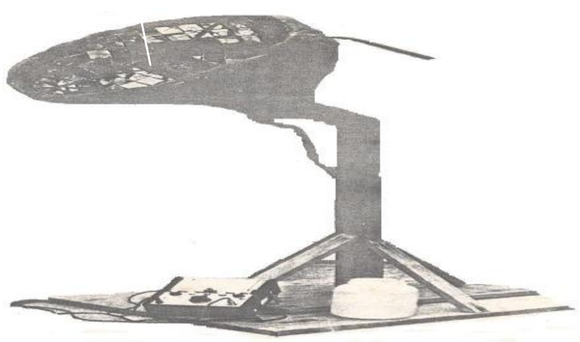

Fig. 4: Complete Experimental Setup

3. RESULTS AND DISCUSSION

3.1 Solar to Electrical Conversion

The experimental setup shown in Fig. 4 was used to intercept solar radiation and the data was collected over duration of three months (March - June).

Study on solar concentrator is not new, what remains a challenge are the concentrator shape or curvature and mirror or lens to concentrate a large area of incident sunlight onto a small area to produce maximum efficiency as radiant heat energy. What is done in this study is an approximation or model of such a system. Electrical power is produced when concentrated light is converted to heat. The photon energy is

$$E = h\nu \qquad (5)$$

and is converted to heat energy

$$Q = mS\Delta T \qquad (6)$$

where m is the mass of the absorber, S is the specific heat capacity and ΔT is the temperature difference between the hot and cold junction for any length of time. The heat can drive a heat engine, usually a steam turbine which if connected to an electrical power generator, can produce electricity as in any thermo - chemical reaction driven process like with a petrochemical fuel.

In the case of a thermocouple, a junction is placed at the point where the sun ray is focused making a hot junction and an adjacent junction away from the sun as the cold junction. The resulting temperature difference leads to development of electromotive force (emf)

$$\text{emf} = -k\Delta T \qquad (7)$$

which drives current through the couple. An array of thermocouples make a thermopile.

The relationship between the emf and temperature difference is linear (Akoshile, 2001;2005) and the temperature gradient produced between the hot thermo junction and the cold junction causes a drift of electrons from the hot junction to the cold junction producing current. The concentrator in this case produced concentration ratio of 91.

One of the fundamental problems associated with the effort to replace conventional energy sources by solar energy is to achieve high temperature (Akoshile, 2005b*)* at low cost. The higher the concentration ratio of the concentrator, the higher the temperature of the hot junction and the more useful the energy collected for heating the thermocouple junction and corresponding conversion to electrical energy generated (Lansing and Dorman, 2009).

3.2 Calibration of Copper – Constantan Thermocouple

The output of a thermocouple is usually of the order of millivolts. In this study, a single thermocouple comprising of constantan and copper wires was used. The calibration was done using standard values taken from Handbook of Chemistry and Physics, 59^{th} Edition. Testing was done with ice-water as the cold junction and measuring corresponding emf as the temperature increases. The measurement made was in good agreement with the standard as shown in the plot of Figure 5. While a single junction responds as shown, multiple junctions will give larger values and multipliers of this result. Using this calibration values, the result observed in this study with a single thermocouple junction was made at high temperature difference between the hot and cold junctions that is well in excess of 100°C.

The linearity justifies equation 8 above using copper – constantan thermocouple.

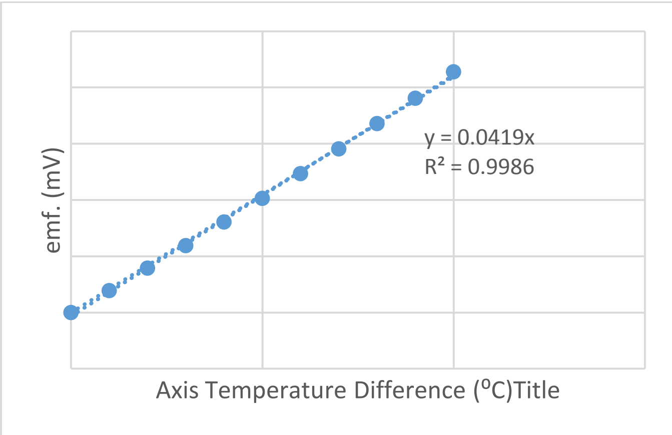

Fig. 5: Calibration Curve of Copper – Constantan Thermocouple (Handbook of Chemistry and Physics, 59^{th} Edition).

3.3 Emf Response from Solar Heated Thermocouple at Changing Time of Day

The result of emf realized as a function of time is shown in figure 6.

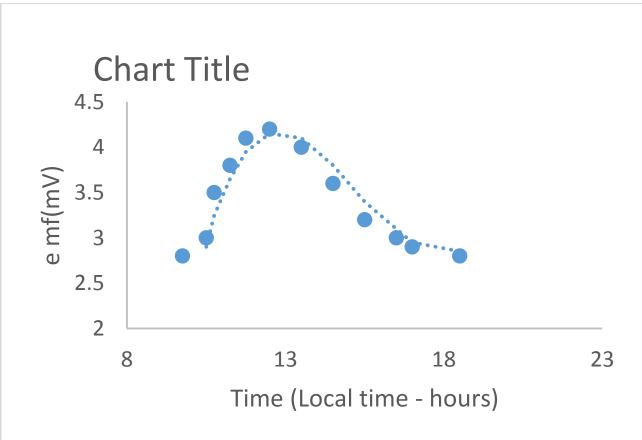

Figure 6: Output electromotive force as a function of time.

It has a peak value of about 4.2mV occurring around 12:30 (Local Time) mid-day on a cloud free day. It is an asymmetric Gaussian curve. It approaches the maximum more sharply than it recedes from it, after. The curve is similar to the plot of shortwave global solar radiation (Pinker et al., 2006) which shows that the intensity of the sun reaching the earth surface is highest when the sun is overhead and this occurs when the emf is maximum. Correspondingly, the temperature is maximum at this point (Bristow, 1984; Akoshile, 2001) and the response emf developed is maximum. The solar to electrical energy conversion is demonstrated and possibility of multiple production of the system is plausible.

3.4 Other Applications

Two sheets of polythene (nylon) spread on a black carbon paper and placed at the focal point of the solar concentrator melted. Existing literature shows that the melting point of polythene is between 150 and 200^{o}C (Don and Robert, 2007). The working fluid of molten salt could be heated to between 150 and 350^{o}C and used as a heat source for power generation system and heating purpose such as cooking and drying. The test on the polythene implies that a temperature within the range quoted above was attained in this study. This means that the equipment could be adapted for several applications involving direct heating without the use of burning fossil fuels and having its attendant atmospheric polluting exhaust or deforestation in the case of wood felling and bush burning (Akoshile, 1991). This technique will produce required heat, convert solar energy to electrical energy and minimize the production of greenhouse gases which constitute environmental pollution in the atmosphere. This is one way of mitigating adverse climate change.

3.5 Cost Comparison

The materials used are locally and readily available. The cost estimate (Table 1) of the materials used is as follows in Nigerian Naira:

Table 1: Cost estimate of the materials used

Material	**Cost (₦)**
Wood	2,000
Cardboard and Paper mold	2,000
Mirror and cutting labor	5,000
Glue	1,000
Wire	1,000
Copper wire	2,500
Constantan wire	3,000
TOTAL	**16,500**

Estimated average insolation of solar radiation reaching earth surface at Ilorin is 300 W.
Then, 1 kW can be obtained from about 3.5 m^2
Area used for study (A) 0.4 m^2.
Then about 8.5 X 0.4 = 3.5 m^2. This implies that less than ₦140,500 will produce about 1 kW of electricity if efficiency is 100 % and N281,000 at 50 %. A 5 kW system will require about ₦702,500.

This price is comparable to solar panel cost for similar wattage. The additional benefit of solar source to fossil fuel or nuclear source or bush burning is that there is no need for continuous fuel consumption. It is durable for well over a decade with no pollution added to the atmosphere, creation of radiation pollution, wild fire or deforestation (Babatunde, 2009). These extra environmental effects and resulting hazards clean-up give extra cost to the use of fossil fuel and nuclear energy in delayed cost and risk to human life. This technique will therefore significantly mitigate atmospheric pollution and the attendant climate change effect.

4. CONCLUSION

The experimental study describes a low-cost method of manufacturing a high temperature solar concentrator and receiver system to mitigate the effect of climate change in energy production system. Findings from the study demonstrated that some of the energy needs of the society could reasonably be met at low cost that is devoid of environmental pollution. The performance of the constructed concentrator-absorber-thermocouple system using locally sourced materials is promising and revealing. The production of electricity (about 4.2 mV) and high temperature range of 150-200^{o}C in the study could be considered as a good starting point which requires better attention for higher performance. The equipment developed in this study is just a model and higher temperature and larger values of emf could be achieved by improving on and modifying the components of the system as a whole, such as increasing the concentrating area of the reflector while reducing the focus area of the absorber in order to obtain larger concentration ratio. Also, the choice of material, design of the receiver and working fluid can be optimized for better performance of the system. In addition, the use of thermopile instead of a single thermocouple will produce higher emf and current. The technique can save the globe of the drift towards increasing disadvantageous climatic change effect.

ACKNOWLEDGEMENT

We wish to acknowledge the support received from the University of Ilorin, Ilorin, Nigeria.

REFERENCES

Abdulrahim, A. T., Diso, I. S. and EL-Jummah, A.M. (2010). Solar Concentrators' Development In Nigeria: A Review. Continental J. Engineering Sciences, Vol. 5 pp 38 – 45.

Akoshile, C.O. (1991). "Mini Solar Pond". Renewable Energy, Vol.1 No. 314 463-467.

Akoshile, C. O. (2001). "Solar Energy Harnessing (S.E.H.) III- Concentrators;" Principles, Measurements and Applications of Solar and Atmospheric Radiation, pp 103 – 118, Unilorin Press, ISBN 978-055-433-5.

Akoshile, C. O. (2005). "Thermopile in Solar to Electrical Conversion and Radiation Measurement;" Nig. Jour. of Solar Energy, Vol. 15, pp. 38-47.

Akoshile, C. O. (2005). "High Temperature Attainment and Level Separation In Mini-solar pond. Nigerian Jour. of Solar Energy, Vol. 15, pp 53-59b.

Aliu, S.A., Kwasi-Effah, C. C. and Otoide, E. O. (2013). Design and Economic Evaluation of a Solar Water Pumping System for Domestic Supply in Nigeria, Nig. J. of Solar Energy, 24: 27 – 30.

Babatunde, E.B., and Aro, T.O. (1990). Characteristics variation of Total, Global, solar radiation at Ilorin, Nigeria, Nig. J. of Solar Energy, 9, pp 157-173.

Babatunde, E.B., Akoshile, C.O., Falaiye, O.A., Willoughby, O.A., Ajibola, T. B., Adimula, I. A. and Aro, T.O. (2009). Observation of bio-effect of SW – global solar radiation in Ilorin in the tropics, Advances in Space Research, Vol. 43, (6): 990-994, Elsevier.

Bristow, K.L. and Campbell, G.S. (1984). The relationship between incoming solar radiation and daily maximum and minimum temperature, Agricultural and Forest Meteorology, 31, pp159-166.

Don, W.G. and Robert, H.P. (2007). Perry's Chemical Engineer's Handbook, 8th Ed. McGraw-Hill. New York.

Ebunlino, P.O.B. and Kwasi-Effah, C. C. (2013). Design and Economic Feasibility of a Solar Powered Ice Maker, Nigerian Journal of Solar Energy, 24. 31-34.

Weast, R.C. Handbook of Chemistry and Physics, 59th Edition, Edition (1978 -1979), Publisher: CRC Press.

Kadiri, T. G., Endurance, O. and Okruzor, E. (2011). Technical Report on Investigation and Assembly of Solar Power Refrigerator, University of Benin, Benin city, Edo state.

Lansin, F. L. and Dorman, J. (2009). High - Efficiency Solar Concentrator. JPL Deep Space Network Progress. 42-45.

Pinker, R. T., Zhao, Y., Akoshile, C., Janowiak, J. and Arkin, P. (2006). "Diurnal and Seasonal Variability of Rainfall in the Sub-Sahedl as seen From Observations, Satellites and Numerical Model," Geo. Res. Lett., Vol. 33, L07806, pp 1 – 4.