OPEN ACCESS
Saudi Journal of Engineering and Technology
Abbreviated Key Title: Saudi J Eng Technol
ISSN 2415-6272 (Print) |ISSN 2415-6264 (Online)
Scholars Middle East Publishers, Dubai, United Arab Emirates
Journal homepage: https://saudijournals.com

Original Research Article

Development of Solar Operated Evaporative Refrigerating System

A. O. Akinola[1*], S. Umar[1], J. F. Eiche[2], A. Akinsade[2]

[1]Department of Mechanical Engineering, the Federal University of Technology, Akure
[2]Department of Mechanical Engineering, Olusegun Agagu University of Science and Technology, Okitipupa

DOI: 10.36348/sjet.2022.v07i06.004 | **Received:** 29.12.2021 | **Accepted:** 06.02.2022 | **Published:** 06.07.2022

***Corresponding author:** A. O. Akinola
Department of Mechanical Engineering, the Federal University of Technology, Akure

Abstract

People in the rural regions of the developing countries where electricity supply is not available are facing the problems of preserving their food through refrigeration. They need affordable and efficient method of food preservation. Therefore, a solar operated refrigerator was designed, constructed and evaluated. The system consists of three major parts, namely: the mild steel box ($0.4\ m \times 0.4\ m \times 0.5\ m$), the clay shell and the wooden box ($0.5\ m \times 0.5\ m \times 0.6\ m$). The mild steel box is enclosed in a clay shell, which is in turn enclosed in a wooden box with four open ducts. The work evaluated convective heat transfer through the ducts and the machine was tested on no load and also by using it to cool 40 kg of water for seven consecutive days over a period of eight hours per day. The results from its performance tests indicated that the system has a cooling process coefficient of performance (COP) of 2.48 and overall coefficient of performance (COP) of 1.64.

Keywords: clay, solar radiation, ambient temperature, duct temperature, wind speed.

INTRODUCTION

The process of removing heat from an enclosed space or from a substance for the purpose of lowering the temperature is known as refrigeration. It is a method of lowering the temperature of substances below that of the surrounding in order to preserve or make them suitable for consumption in the nearest future [1-3]. In the industrialized nations and affluent regions of the developing world, refrigeration is chiefly used to store foodstuffs at low temperatures, thus inhibiting the destructive action of bacteria, yeast, and mold. Many perishable products can be frozen, permitting them to be kept for months and even years with little loss in nutritional values or flavour or change in appearance [4]. Refrigeration system mainly works on reversed Carnot cycle and it is the reversed system of heat engine as its input is work and output is cooling effect. Total heat reduction is proportional to the work input given to the system according to the 1st law of thermodynamics [5]. The basic Refrigeration system which is called "vapour-compression system" is the simplest of all the refrigeration systems and is widely used for its simplicity, efficiency and compactness and the system uses different refrigerants according to the requirements [6]. The basic components of a refrigerator are: compressor, condenser, an expansion device and evaporator as shown in Fig. 1.

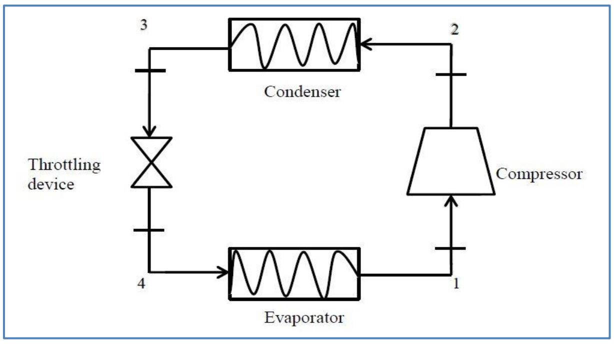


Fig-1: Schematic diagram of a vapour compression refrigeration system [7]

Non-conventional refrigerating system also works on the same principle as vapour compression system, the only difference is that, instead of compressor and condenser, it employs evaporation mode of heat transfer. The non-conventional refrigerating systems offer many advantages over vapour compression refrigeration. They are entirely solid-state, rugged, reliable and quiet due to absence of moving parts. They use no ozone depleting agents like chlorofluorocarbons, offering a more environmentally responsible alternative to conventional refrigeration. They can be extremely compact, much more so than compressor-based systems [8], and example of such is solar operated evaporative refrigerating system.

Solar energy has emerged as a vital source of energy over the past two or three decades. It is a renewable source of energy which can be generated again and again and it is widely used for a variety of industrial and domestic applications. Some systems based on a solar collector are designed to collect the sun's energy and to convert it into either electrical power or thermal energy, thereby reducing overdependence on electricity [9].

Many researches have been done on the application of solar energy for optimum refrigeration. For instance, [10] studied an air-conditioning system utilizing solar energy. The results of his findings indicated that the system would generally be more efficient, cost wise, if it was used to provide both heating and cooling requirements in the building it serves. The research gave fundamental knowledge on a solar absorption cooling systems with the absorption pair of lithium bromide and water.

In their work, [11] reported the performance of a solar refrigeration system operating with $NH_3/SrCl_2$. The overall efficiency defined as the cooling capacity to the solar radiation received by the solar collectors of the cooling system varied from 0.05 to 0.08 [12]. Published the experimental study on dynamic performance of a flat-plate solar solid-adsorption refrigeration for ice maker operating with activated carbon/methanol. The experimental results showed that this machine can produce 4 – 5 kg of ice after receiving 14 –16 MJ of radiation energy with a surface area of 0.75 m^2, while producing 7–10 kg of ice after receiving 28 – 30 MJ of radiation energy with 1.5 m^2.

Hildbrand *et al.*, [13] reported the results of the performance of an adsorptive solar refrigerator operating with the adsorption pair silica gel plus water. Cylindrical tubes function as both the adsorbed system and the solar collector. The results showed that the gross solar coefficient of performance defined by the authors varied between 0.1 and 0.25 with a mean value of 0.16. Rivera *et al*., [4] published a paper about the development of a solar intermittent system operating with the ammonia/lithium nitrate mixture. The authors reported that solar coefficients of performance as high as 0.08 can be obtained with the developed system.

In their work, [14] developed a solar-operated mobile refrigerator. It was powered by a 12 volts DC battery operated 700 W photovoltaic system, and 220v/50 Hz 400 W 12 V power inverter. The system had an overall refrigerating efficiency of 79.36%.

In Nigeria where electricity supply is not available, storage of food through refrigeration becomes impossible. People in the rural regions of the country face problems of preserving fruits and vegetables which then result to both material and economic losses. This therefore, calls for the need to develop a functional non-conventional solar operated refrigerator (electricity free) that would perform the same functions as the modern refrigerators.

MATERIALS AND METHODS

Materials

The major materials used for the developed system are Isan clay from Isan-Ekiti, Ekiti State, mild steel and wood. The reason for using Isan clay for the developed system is due to its excellent working properties as reported by [15], and presented in Table 1. Mild steel was used due to its tensile strength and strength to withstand the load of the items to be refrigerated.

Table-1: Physicochemical properties of Isan clay

Physicochemical properties of Isan clay	
Refractoriness	High
Cold compressive strength	Moderate
Thermal shock resistance	High
Bulk density	High
Apparent porosity	High
Linear shrinkage value	Low
Coefficient of thermal linear expansion	High
AL2O3	29.79
SiO2	46.50
CaO	2.09
MgO	0.96
Fe2O3	1.18
Na2O	0.13
TiO2	1.04
K2O	0.11
LOI	16.20
GFN	44

Source: [15]

Design Analysis

The design focused on the working conditions of the machine. The important components considered are: the mild steel box, the clay shell and the wooden box. These components work together to get a desired effect. The summary of solar operated refrigerator design analysis is shown in Table 2.

Table-2: Summary of solar powered refrigerator design analysis

S/N	Components	Design Factors	Mathematical Formula Used	Design Values
1	Refrigerating Space	Total surface area	$A_s = [2(LH) + 2(LB) + 2(HB)]$	1.7 m^3
		Volume	$V_t = [(L-2t)(B-2t)(H-2t)]$	0.0681 m^3
2	Refrigeration load estimation	Product load	$Q_{product} = \frac{m_w C_{p.w}(T_i - T_f)}{\Delta t_c}$	52.76 W
		Air Reynolds Number	$Re_a = \frac{d\ell_a V}{\mu_a}$	197126.4368
		Air Prandt's Number	$Pr_a = \frac{C_{pa}\mu_a}{K_a}$	0.6822
		Air Nusselts Number	$N_{ua} = C\ Re_a{}^n Pr_a{}^{1/3}$	428.3398717
		Co-efficient of heat transfer of air	$h_a = \frac{K_a N_{ua}}{d}$	12.3589 $W / m^2.K$
		Water Reynolds Number	$Re_w = \frac{d\ \ell_w V}{\mu_w}$	364093.96
		Water Prandt Number	$Pr_w = \frac{C_{pw}\mu_w}{k_w}$	6.259
		Water Nusselt Number	$Nu_w = C\ Re_w{}^n Pr_w{}^{1/3}$	1469.3782
		Co.efficient of heat transfer of air	$h_w = \frac{Nu_w k_w}{d}$	899.619 $W / m^2.K$
		Overall co-efficient of heat transfer	$U = \frac{1}{(\frac{1}{h_a} + \frac{x_w}{K_w} + \frac{x_c}{K_c} + \frac{x_{ms}}{K_{ms}} + \frac{1}{h_w})}$	12.1848 $W / m^2.K$
		Wall gain load	$Q_{wall} = A_s U \Delta t$	642.1179 W
		Heat Transfer	$Q = \dot{m}\ cp \Delta t$	0.373127475 kJ / s
		Heat gain by radiation	$Q_{radiation} = \Sigma A_s \sigma (T_i{}^4 - T_f{}^4)$	115.94 W
		Total cooling load	$Q_{tcl} = Q_{product} + Q_{wall} + Q_{radiation}$	900.52369 W
3	Capacity	Required equipment capacity (REC)	$REC = \frac{Q_{tcl} \times 24\ hours}{the\ operating\ time\ (10\ hours)}$	2.161256856 kW

Description of the Solar Operated Refrigerator

The refrigerating system is made up of two boxes – one placed inside the other. The outer box is made of wood ($0.5\ m \times 0.5\ m \times 0.6\ m$) with rectangular holes drilled on the sides. The inner box is made of galvanized metal sheet ($0.4\ m \times 0.4\ m \times 0.5\ m$). The gap between the inner and the outer boxes is filled with clay because it can be soaked with water. The top surface of the mild steel box is covered with a flat plate. The bottom and four sides of the mild steel box are insulated by 50 mm thickness of clay. As the aperture on the upper surface of the mild steel box absorbed and emitted heat into the mild steel cabinet, the walls of the cabinet which are also painted black absorbed the heat emitted and the heat generated by the produce inside the cabinet. The sun's rays heat the wet clay and it in turn loses heat through evaporation. As the water evaporates, the heat from inside the metal box is being transmitted to the clay through conduction because the clay and the metal box are in contact. Once the clay is wet, the heat flow would be continuous thereby keeping the system working. The heat absorbed by the walls of the cabinet is retained by the insulator (clay) and is then vented out through the four open ducts by convective heat transfer as air flows across the outer layer of the refrigerator, thereby providing adequate cooling. The developed system when tested on no load and the experimental set up are shown in Plates 1 and 2 respectively while Fig. 1 shows the exploded view.

Plate-1: On no load testing of the system

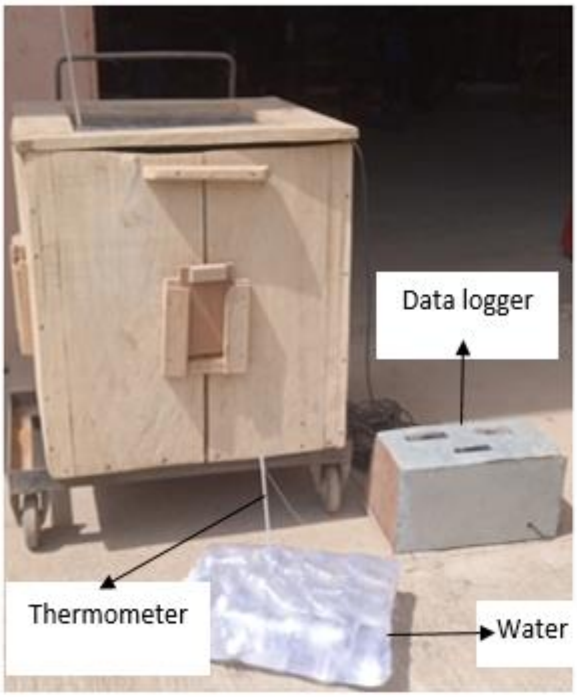
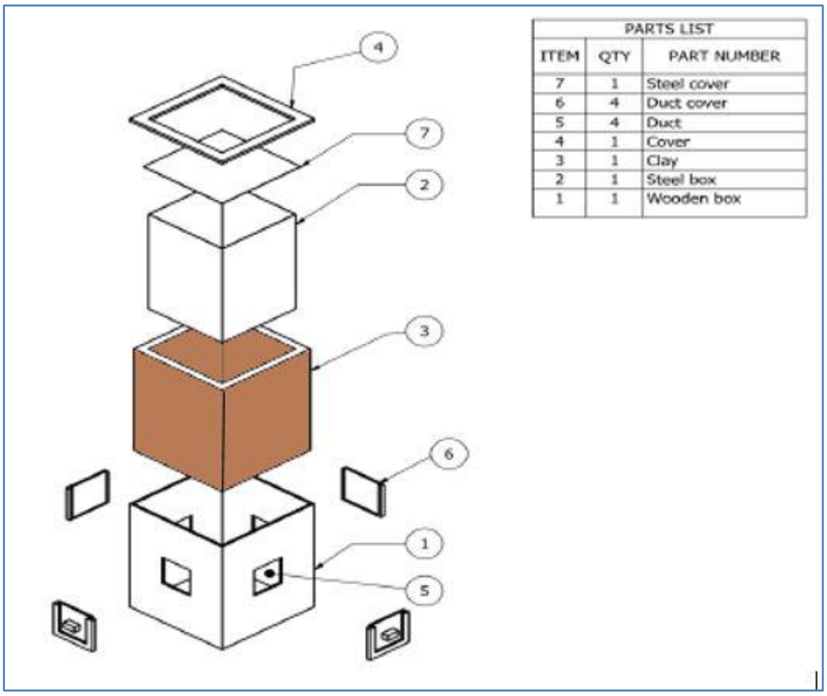


Plate-2: Experimental set up



PARTS LIST		
ITEM	QTY	PART NUMBER
7	1	Steel cover
6	4	Duct cover
5	4	Duct
4	1	Cover
3	1	Clay
2	1	Steel box
1	1	Wooden box

Fig-1: Exploded view of the developed system

RESULTS AND DISCUSSION

The machine was first tested on no load before it was used to cool 40 kg of water for seven consecutive days over period of 8 hours per day (10:00 – 15:00). The locally made sensors were connected to data logger for easy collection and collation of data. Measured parameters include: time (hr), ambient temperature (°C), relative humidity, solar radiation, wind speed, cabinet temperature (°C) and duct temperature (°C). The results of the machine operation parameters were used to carry out the performance evaluation of the machine. Graphs were plotted relating the effects of these parameters on the cabinet temperature of the developed system as shown in Fig. 2 to 4.

Average cabinet temperature on no load is 2.63℃
Average ambient temperature is 26.54 ℃
Difference in average ambient and cabinet temperature is 23.91℃
Mass of water refrigerated m_w is 40 kg

Initial temperature of water T_i is 27 °C
Average final temperature of refrigerated water T_f is 2.86 °C
Average temperature of water under the sun T_s is 36.74 °C
Specific heat capacity of water $C_{p.w}$ is 4.22 kJ/kgK
Mean direct radiation (MDR) is 537.63 W/m^2
Average experiment time is 8 hours
Length of aperture $l = 0.4\ m$

$Amount\ of\ cooling\ obtained\ ACO = m_w\, C_{p.w}\,(T_i - T_f) = 4074.832$ kJ

Area of aperture opening to direct radiation $A_R = l^2 = 0.16\ m^2$

$Amount\ of\ cooling\ available\ in\ the\ surrounding\ ACAS = m_w\, C_{p.w}\,(T_s - T_i) = 1644.112$ kJ

$Total\ direct\ radiation\ TDR = 8\ hrs(3600)(MDR)(A_R) = 2477.4\ kJ$

$$COP\ cooling\ process = \frac{ACO}{ACAS} = 2.48$$

$$Overall\ COP = \frac{ACO}{TDR} = 1.64$$

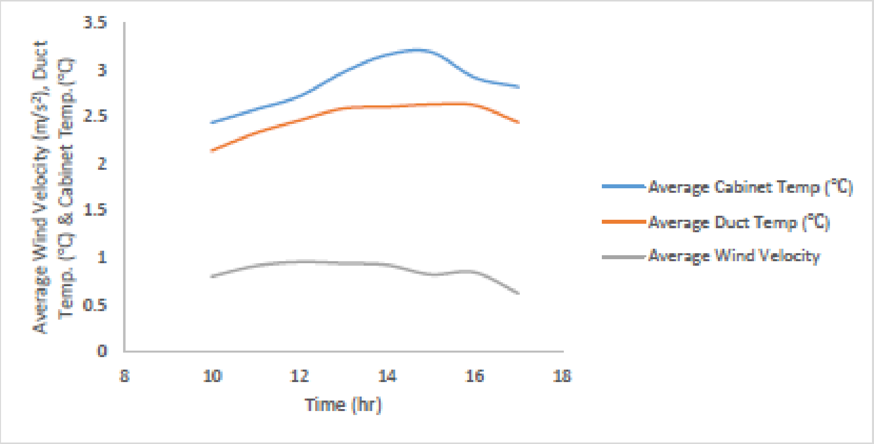


Fig-2: Graph of average cabinet temperature, duct temperature and wind velocity vs time

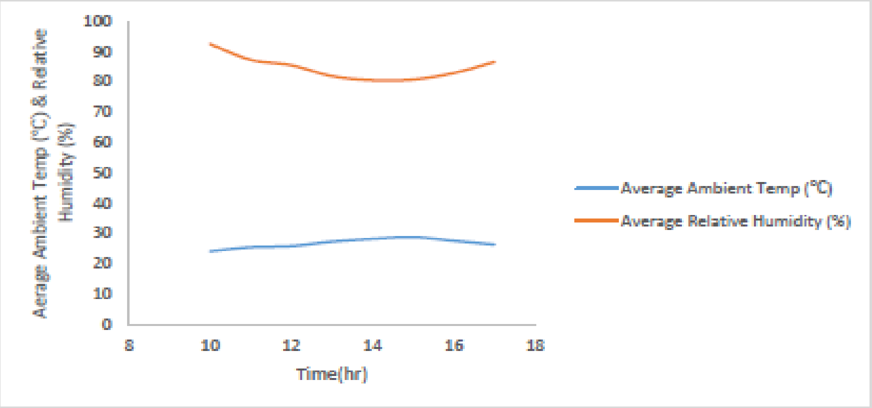


Fig. 3: Graph of average ambient temperature and relative humidity vs time

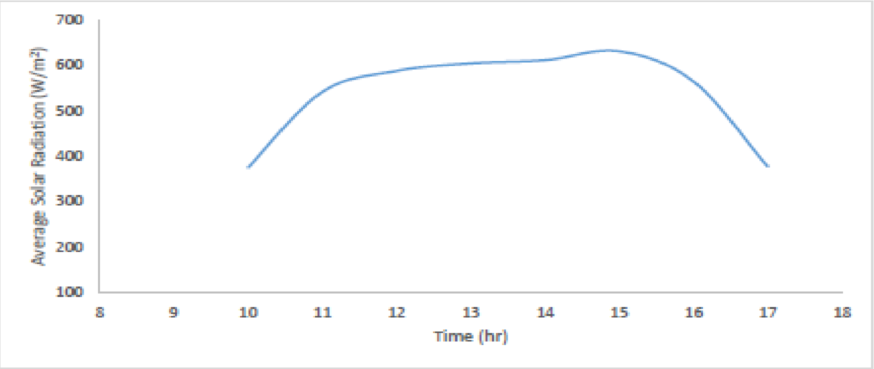


Fig-4: Graph of average solar radiation vs time

The results from the no load testing indicated that the solar powered refrigerator reduced the temperature of the compartment far below that of ambient and surrounding effectively. Against an average ambient temperature of 26.54^{o}C, the cabinet temperature was reduced to an average of 2.63^{o}C Also, the results from its performance evaluation showed that the COP cooling process is 2.48 while overall COP is 1.64 when 40 kg of water was refrigerated for consecutive seven days over period of eight hours per day (10.00 AM -5.00 PM). Fig. 2 shows the variation of cabinet temperature, duct temperature and wind velocity with time. The maximum cabinet temperature was 3.2 ℃ at 15:00 and minimum was 2.4 ℃ at 10:00; the maximum duct temperature was 2.64 ℃ at 15:00 and minimum was 2.1℃ at 10:00; the maximum wind velocity was 0.958 m/s at 12:00 and minimum was 0.627 m/s at 5:00. The maximum ambient temperature was 28.84℃ at 15:00 and the minimum was 24.14℃ at 10:00, the maximum relative humidity was 92.56 % at 10:00 and minimum was 80.625 % at 14:00 while the maximum solar radiation was 632.022 W/m^2 at 15:00 and minimum was 375.837 W/m^2 at 10:00 as shown in Fig. 3 and 4 respectively. These results showed that, at a very high solar radiation and ambient temperature, the system was still able to maintain 3.1 ℃ cabinet temperature but maximum cooling of 2.5 ℃ and below was achieved at a low ambient temperature, low solar radiation, medium wind velocity and very high relative humidity.

CONCLUSION

A solar operated evaporative (non-conventional) refrigerating system was designed, fabricated and evaluated. All the materials used for its construction were locally sourced. The non-conventional refrigerating system was able to refrigerate effectively and hence reduced both wastage and deterioration of perishable food items. The overall coefficient of performance of the machine was 1.64, and a cooling process COP was 2.48. This refrigerator can be used by farmers in warm climates preserve their produce for a longer time and keep insects away. It can also be used in the market for cooling and preservation. Such small-scale stand-alone system can suitably be used in many rural regions where electricity is unreliable or non-existent.

REFERENCES

1. Althouse A.D., Turnquist C.H., & Branco A.F. (1978). "Modern Refrigeration and Air Conditioning". Good Heart Willox Co., London
2. Fapetu, O. P. (2002). "Principle and Practice of Refrigeration" Volume 1, Pin-Funky Press, Akure, Nigeria.
3. Akinola, A. O., Akintayo, T. C., & Kuti, O. A. (2008). "Development of a Hawking Refrigerator". *FUTA Journal of Engineering and Engineering Technology,* FUTAJEET, Vol. 6, No 1: 88 – 96
4. Rivera, W., Moreno-Quintanar, G., Rivera, C. O., Best, R., & Martínez, F. (2011): "Evaluation of A Solar Intermittent Refrigeration System for Ice Production Operating with Ammonia/Lithium Nitrate". *Solar Energy* 85(1): 8-45.
5. Khurmi, R. S., & Gupta, J. K. (2010). A text book on refrigeration and air-conditioning (Economy Ed.). ISBN-13:978-81-219-2781-9.
6. Anyanwu, E. E. (2004): "Design and measured performance of a porous evaporative cooler for preservation of fruits and vegetables" *Energy Conversion and Management* (45) 2187 – 2195.
7. Dossat, R. J., & Horan, T. J. (2002). Principle of Refrigeration. Prentice Hall, New Jerson, Usa. Fifth Edition, ISBN 0-13-027270-1 Ppl-454.
8. Date, A.W. (2012). "Heat and Mass transfer analysis of a clay-pot refrigerator" *International Journal of Heat and Mass Transfer* 55: 3977-3983
9. Harish, H., & Gowda, Y.T.K. (2014): "Thermal Analysis of Clay Pot in Pot Refrigerator" *International Journal of Modern Engineering Research* (IJMER), 4(9): 50-55
10. Mittal, V. (2005). "The study of solar absorption air-conditioning systems" *Journal of Energy in Southern Africa*, Vol 16, No.- 4, pp. 59-66.
11. Erhard, A., Spindler K., Hahne, T. (1998): "Test and simulation of a solar powered solid sorption cooling machine", *International Journal of Refrigeration, 21*(2); 133-141
12. Li, M., Wan g, R. Z, Xu, Y. X., Wu, J. Y., Dieng, A. O. (2002). "Experimental study on dynamic performance analysis of a flat-plate solar solid-adsorption refrigeration for ice maker". *Renewable Energy* 27: 211–221.
13. Hildbrand, C., Dind P., Pons M., Buchter F. (2004): "A new solar powered adsorption refrigerator with high performance". *Solar Energy* 77: 311–318.
14. Akinola, A. O., Mogaji, T. S., & Adewole, K. A. (2015). "Development of a Solar-Powered Mobile Refrigerator" *International Journal of Emerging Technology and Advanced Engineering* (IJETAE). Vol. 5, Issue 9, 1 – 6
15. Omotoyinbo, J. A., & Oluwole, O. O. (2008). Working properties of some selected refractory clay deposits in South Western Nigeria.