International Journal of
Advances in Scientific Research and Engineering (ijasre)

E-ISSN : 2454-8006

DOI: 10.31695/IJASRE.2019.33634

Volume 5, Issue 12
December - 2019

Design and Performance Testing of a Solar Water Heater

Oselen Imafidon J., Oseiga Omijie V. and Ikpe Aniekan E.

Department of Mechanical Engineering

University of Benin

Benin City, Edo State

Nigeria

ABSTRACT

This work combines flow by natural convection and forced flow in the design of a solar water heater. The solar water heater was designed such that the entire process was powered by solar energy. This study is focused on the efficiency of the system and the output temperature obtained in Edo State, Nigeria, at Latitude 6.54^{0}N of the equator. Experimental tests were conducted in the mid rainy season, through the month of June 2017. The result showed the maximum heat rise of 110^C and a minimum of 60^C. However, the results displayed are the average of each week of the month of June 2017. The overall efficiency of the system was found to be 54.54%, indicating that more improvement is required for increased efficiency and optimum heat supply.

Key Words: *Solar energy, Water heater, Design, Solar collector, Absorber plate.*

1. INTRODUCTION

Energy plays a vital role in the growth, progress and development of any nation. Sources of energy are majorly divided into two forms: non-renewable and renewable sources. Energy sources are considered non-renewable, if they cannot be replenished in a short period of time while renewable energy sources are energy sources that can be replenished naturally, for example, solar, wind, biomass, hydropower, etc. Man over time has developed different means of energy sources and technology applicable for heating purposes to achieve its wants. Some of these technology though is primitive in terms of application are still used in some parts of the world.

One promising source of renewable energy is solar energy. Water heating by solar energy for domestic use is one of the most successful and feasible applications of solar energy [1]. Other areas of application of solar energy include solar drying, electricity generation using photovoltaic cells, solar cooling and refrigeration, solar still (or solar distillation) and solar cooking [2]. Solar energy is a combination of photon and thermal energy captured and applied over a range of ever-evolving technologies such as solar heating, solar thermal energy, molten salt power plants, artificial photosynthesis etc. Solar radiation being abundantly present in Nigeria is one area of focus among the renewable energy resources and this can be harnessed for heating water for both domestic and industrial purposes. The mean annual average of total solar radiation varies from about 3.5 kWhm-2day-1 in the coastal latitudes to about 7 kWhm-2 day-1 along the semi-arid areas in the far North [3]. On the average, the country receives solar radiation at the level of about 19.8 MJm-2 day-1. Average sunshine hours are estimated at 6hrs per day. Solar radiation is fairly well distributed. The minimum average is about 3.55 kWhm-2day-1 in Katsina in January and 3.4 kWhm-2day-1 for Calabar in August and the maximum average is 8.0 kWhm-2day-1 for Nguru in May [3]. The various energy centres are making giant strides in production of solar energy technologies for direct harnessing of solar energy since the country is situated in the high solar radiation belt of the world [4].

Solar thermal technologies that have been disseminated in Africa countries include solar water heaters, solar cookers, solar stills and solar dryers [5]. Solar water heaters are used for heating water in residential or commercial premises. Solar dryers in Africa are mainly used for drying fruits, vegetables and fish, and solar cookers and ovens are used in household and institution for cooking [5].

Thermal energy storage (TES) is achieved with greatly differing technologies that collectively accommodate a wide range of needs. Solar Energy in the form of Irradiative heat is absorbed by the Solar Collectors via the Black body absorber. This heat energy is stored as sensible heat in the water contained in the storage tank. The sensible heat storage uses the heat capacity and the change in temperature of the water during the process of charging and discharging the system. The high heat capacity and density of water makes it a good heat storage fluid [6].

A Solar Water Heater is a system that produces hot water using thermal energy obtained from the sun or environment. Heat energy is a form of energy which transfers among particles in a substance (or system) by means of kinetic energy of those particles. In other words, kinetic theory suggests, the heat is transferred by the friction of particles bouncing into each other. In this study, a solar water heating system was designed and tested to determine necessary working conditions and efficiency of the system.

2.0 MATERIALS AND METHODS

The materials and methods use to achieve the aim of this study is presented as follows;

2.1 Materials

The materials employed in the design of a solar water heater in this study are presented in Table 1.

Table1: Materials employed in the design of the Solar Water Heater

Materials	Methods
Solar Pre-heat	Refers to the pre-heating of a water supply using thermal solar collectors. This water can then be stored for later use reducing the amount of energy required to heat the water from ground temperature.
Solar Collector	This is a specially engineered panel or collector where the fluid passes through copper tubes and where it is heated by solar energy.
Solar thermal collector	A collector is a device for trapping solar radiation from the sun. Solar thermal collector collects and stores thermal energy (heat) by absorbing sunlight
Storage Tank	This is an insulated water tank specially designed for the storage of heated water.
Thermosiphon	The automatic circulation of waters of different temperature gradients. As the temperature of a fluid rises, it becomes less dense and will rise while cold fluid is denser and falls, this phenomenon is called thermosiphoning. Thermosiphon solar water heaters are often referred to as “close-coupled” and do not require electric pumps to circulate the water.
Pumped System	This refers to a “pumped” or “split” solar hot water system that uses a small pump to circulate water up to a series of roof-mounted solar collectors for heating.
Absorber Plate	This is the part of the collector that collects the solar energy and transforms it to heat. The absorber plate is treated with a special coating, designed to attract and retain the heat energy from the sun.
Selective Surface	This is a special treatment given to the surface of a thermal collector absorber plate, allowing it collect the optimum amount of heat energy from the sun.
Booster	A supplementary heat source in a solar hot water or solar pre-heat system; typically electricity or gas.
Continuous Flow Gas Water Heater	This is a gas fuelled water heater that only ignites to heat ‘on demand’, as the water flows through it.
Heat Exchanger	A heat exchanger is a piece of equipment designed for the efficient heat transfer from one medium to another. Heat exchangers are often used in areas of poor water quality of where multiple heat sources are required.
Close-coupled Solar Hot Water	Refers to thermosiphon system where a collector is closely mounted to the hot water storage tank.
Closed loop	Refers to a system using a heat exchange fluid to heat the potable water via a heat exchanger. In these systems there is no mixing of fluids between the heat source and the heated water. Can be either a thermos-siphon or pumped system.

DOI: 10.31695/IJASRE.2019.33634

Open Loop	It is a system where the potable water is in direct contact with the thermal collector and water storage tank. It can be either a thermo-siphon or pumped system.
Solar (Differential) Controller	It is an electrical device that reads the difference between the Collector temperature and the stored water temperature, to regulate the solar input by controlling the pump operation in a split system.
Element	A thermostatically controlled electrical element used to heat the stored water above the level of solar contribution.
Glycol (Heat Exchange Fluid)	Transfers the solar energy to the stored potable water via a heat exchanger, prevents freezing or clogging of collectors in bad water areas.

Table 2: Bill of Engineering Materials and Evaluation

S/N	Component	Material	Dimension/ Capacity	Quantity
1	Absorber Plate	Aluminum	79cm x 40cm	2
2	Battery		12V/18AH	1
3	Collector Casing	Wood	82cm x 45cm x 13cm	1
4	Cylinder Supply tank	Mild Steel	55cm x 24cm	1
5	Flexible hose	Polyethene	0.5cm	1
6	Frame/Stand	Mild Steel	158cm x57 cm x 37cm	1
7	Heat transfer serpentine tube	Copper	4 segments L= 40cm D_{tube} = 1cm R_{turn}=17cm	2
8	Pump		0.25hp DC	1
9	Solar panel		130W, 24V	1
10	Switch/Controller		15-290A 125V-250V	1
11	Tank Insulation	Foam	75.4cm x 55cmx 8cm	1
12	Transparent Collector Cover	Glass	80cm x 43cm	1

2.2 Method

Solar radiation is energy in the form of electromagnetic radiation from the infrared (long) to the ultraviolet (short) wavelengths. The average solar energy that reaches the Earth's surface (solar constant) is about 1,000 watts per square meter under clear skies, depending on the weather conditions, location and orientation [7]. A solar water heating system was designed such that the absorber plates collects the solar energy and transforms it to heat. The heat absorbed is then transferred to a fluid which is usually water or a glycol mixture, flowing through the collector. Before the experimental set-up was put together, the necessary design requirements were specified. As shown in Figure 1, the design drawing was represented in a 3D view for proper understanding and ease of assembly. Most materials constituting the design set-up were bought from the open market and worked on to suite the purpose.

2.3 Design Requirement

The following criteria were considered as the major design requirements for the solar water heating system;

i. The solar water heater must be durable and reliable.
ii. The cost of manufacturing and maintenance of the solar water heater should be low.
iii. The solar water heater should be easy to fabricate, install, control and maintain.
iv. The solar water heater should be manufactured with locally sourced materials.

2.4 Development of Design Concept

As shown in Figure 1, the solar heater design concept combines flow by natural convection and by forced convection. In the setup, water in a cylindrical tank from a reservoir is made to flow to copper piping tubes on top of a black body aluminium material enclosed in a rectangular box with a glass top. The black body traps the energy from sunlight and heats the copper piping

DOI: 10.31695/IJASRE.2019.33634

containing the cold water. The heated water becomes less dense and runs into another piping at the bottom surface of the black body material and is further heated due to heat flow by conduction. A pump powered by solar panel is used to assist the thermos syphon process when the intensity of the sun is not high enough in order to obtain already heated water trapped in the solar collector. The process is relatively faster and gives high temperature in a short time interval. Also, due to the thermal storage ability by the black body material, water could still be heated to some degree at night. However, the major setback of the design concept is its high cost of set up, which was compensated for by the advantages of the system.

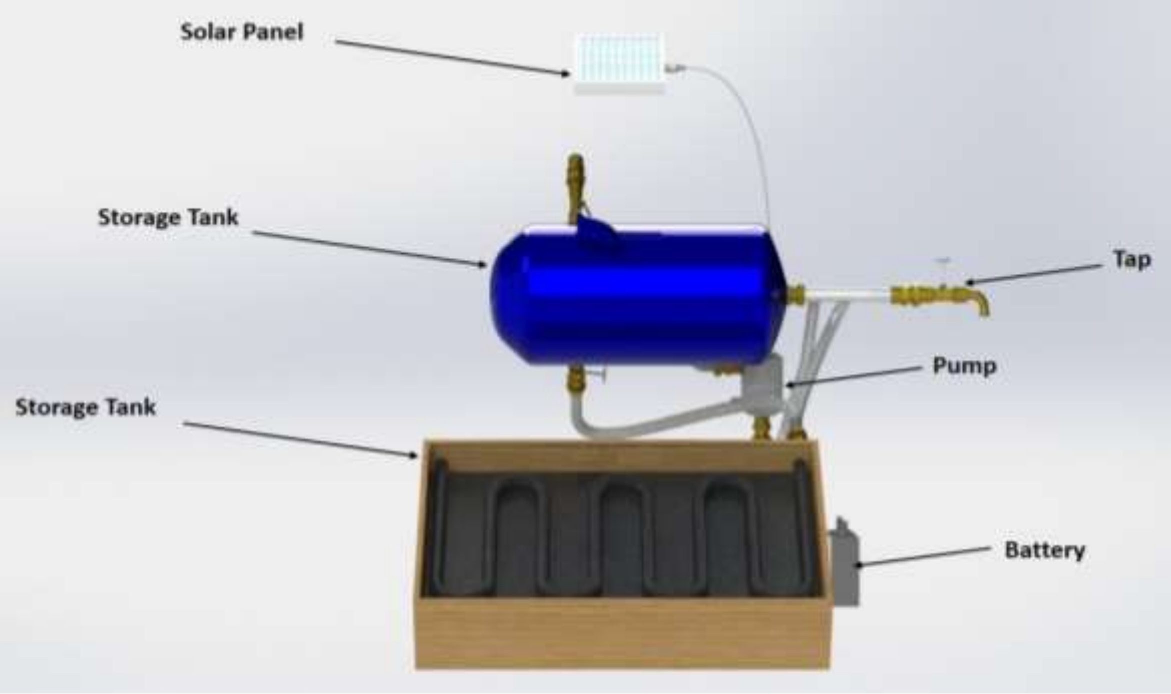

Figure1: Design Set-up of a Solar water heater

2.5 Design Calculations

Collector area (A_C) Is the ratio of the quantity of heat required (Q_w) to raise the temperature of water from T_{in} to T_{out} to the energy absorbed by the collector over a specified period of time [8]. The sizing of the collector area is according to the hot water demand. The heat requirement is given by Equation (1);

$$Q = mc_{pw}(T_{hot} - T_{cold}) \quad (1)$$

Where Q = Quantity of heat in Joules, m = Mass of the water in kg, c_{pw}= specific heat capacity of the water J/kg/K , T_{hot} = Hot water temperature desired in ^{0}C, T_{cold}= Cold water temperature in ^{0}C.

Since $$Density = \frac{Mass}{Volume} \quad (2)$$

$$Mass = Density \times Volume \quad (3)$$

$$m = \rho V \quad (4)$$

Substitute for mass in Equation (1) gives the expression in Equation (5);

$$Q = \rho V c_{pw}(T_{hot} - T_{cold}) \quad (5)$$

Where ρ = density of water = 1000kg/m^3, V= volume of water per day = 30 litres = 0.03m^3

The collector area is given by Equation (6)

$$A_c = \frac{Q}{ntI} \quad (6)$$

Where Q = Quantity of heat (joules), I = solar radiation (W/m^2) = 1,470, n = Efficiency (%) = 40, t = Heating time (sec)

To obtain a temperature of 80^{0}C i.e T_{hot} = 80 ^{0}C

$$A_c = \frac{1000 \, X \, 0.03 \, X \, 4200 \, X \, (80-20)}{0.4 \, X (6 \, X \, 3600) X \, 1470}$$

A_C= 0.5952m^{2}approx 0.6m^2

DOI: 10.31695/IJASRE.2019.33634

Mass flow rate of water within the collector plate area is given by Equation (7);

$$M_f = \frac{mass}{time} \tag{7}$$

$$M_f = \frac{\mu \times \mathrm{Re} \times \pi \mathrm{D}}{4} \tag{8}$$

At 80 ^{0}C, ρ = 971.82kg/m^3, μ = 351 x 10^{-6}kg/ms, D = 0.01m, Velocity of fluid flow, u = 0.15m/s^2

$$\mathrm{Re} = \frac{\rho u D}{\mu} = \frac{971.8x\ 0.15\ x\ 0.01}{351\ x\ 10^{-6}} = 4152.99 \text{ (Laminar Flow)}$$

$$M_f = \frac{351\ \ x\ 10^{-6}\ x\ 4152.99 \times \pi \times 0.01}{4} = 0.01145\text{kg/s}$$

Under steady state condition, the heat loss Q_l from the absorber plate to the glass cover is given by Equation (9);

$$Q_l = UA_C\Delta T \tag{9}$$

Where U is the heat loss coefficient due to both convection and radiation from the absorber plate and glass cover as shown in Figure 1 of the thermal resistance network.

A$_c$ =0.6m^2

ΔT = the temperature difference. = Temperature of Aluminium (T$_{\text{aluminium}}$) -

Temperature of Glass (T$_{\text{glass}}$) = 100^{0}C - 50^{0}C = 373.15k – 323.15k = 50^{0}C, $Q_l = UA_C\Delta T$

$$U = \frac{1}{k_{aluminium}} + \frac{1}{h_{air}} + \frac{1}{k_{glass}} \tag{10}$$

$k_{aluminium}$ = 205W/mk

Convective heat transfer for Air at Laminar flow (h_{air}) = 0.8476W/m^{2}k

Thermal conductivity for Glass (k_{glass}) = 0.96 W/mk

The convective heat transfer coefficient between the absorber plate and glass cover is calculated from the Nusselt number obtained using equation given by (Hollands et al year).

$$Nu = 1 + 1.44\left[1 - \frac{1708}{\cos\beta.Ra}\right]\left[1 - \frac{\sin(1.8\beta)^{1.6}.1708}{\cos\beta.Ra}\right] + \left[\left(\frac{\cos\beta.Ra}{5830}\right)^{1/3} - 1\right] \tag{11}$$

$$\text{Where } Ra = \frac{g\beta(\Delta T)l^3}{v^2} \times Pr \tag{12}$$

For Air at 100^{0}C and 1 atm, g = 9.81m/s^2, Pr = 0.692, L = L$_c$ = 0.79m, μ = 2.181 x 10^{-5}kg/ms

P = 0.9413kg/m^3.

$$v = \frac{\mu}{\rho} = \frac{2.181 \text{ x } 10^{-5}}{0.9413} = 2.317 \text{ x } 10^{-5}\text{m}^2\text{/s}$$

K = 3.186 x 10^{-5}kW/mK

$$\beta = \frac{1}{323.15} = 0.003095\text{k}^{-1}$$

$$Ra = \frac{9.81\ x\ 0.003095 \text{ x } (50)\ x\ 0.79^3}{(2.317 \text{ x } 10^{-5})^2} \times 0.692 = 2235096024$$

$$Nu = 1 + 1.44\left[1 - \frac{1708}{\cos\ 0.003095\ x\ 2.235\ x\ 10^6}\right]\left[1 - \frac{\sin(1.8\ x\ 0.003095)^{1.6}\ x\ 1708}{\cos 0.003095\ x\ 2.235\ x\ 10^6}\right] + \left[\left(\frac{\cos 0.003095\ x\ 2.235\ x\ 10^6}{5830}\right)^{1/3} - 1\right] = 21.018$$

$$\mathrm{Nu} = \frac{h_{air\ \ x\ L}}{k}$$

$$\mathrm{h}_{\mathrm{air}} = \frac{Nu\ x\ K}{L} = \frac{21.018 \text{ x } 3.186 \text{ x } 10^{-5}}{0.79} = 0.8476\text{W/m}^2\text{k}$$

$$U = \frac{1}{k_{aluminium}} + \frac{1}{h_{air}} + \frac{1}{k_{glass}} = \frac{1}{205} + \frac{1}{0.8476} + \frac{1}{0.96} = 2.2263\text{W/m}^2\text{K}$$

Therefore,$Q_l = UA_C\Delta T =$ 2.2263 x 0.6 x 50 = 66.79 J

Assuming Back and edge losses are negligible.

DOI: 10.31695/IJASRE.2019.33634

$$Q_u = A_c(S - U\Delta T)$$

$$Q_u = 0.6(1470 - 2.2263 * 60)$$

$$Q_u = 801.8532 \text{ J}$$

Therefore, the actual efficiency of the collector

$$\eta = \frac{Q_u}{It} = \frac{801.8532}{1470} = 0.5454$$

3.0 RESULTS AND DISCUSSION

After the fabrication was completed, the solar water heater was tested on open field in Benin-City, where the solar radiation available at any time will not be inhibited. The result of tests is as follows;

Table 3: Heat absorbed and Temperature gain of hot water for June, 2017

		Time of the day			
		09:00:00 AM	11:00:00 AM	01:00:00 PM	03:00:00 PM
Week 1	T_{in} (^{0}C)	26	26	26	26
	T_{out} (^{0}C)	26.5	27	29	28.5
	Q (KJ)	63	126	378	315
	Tgain(^{0}C)	0.5	1	3	2.5
Week 2	T_{in} (^{0}C)	27	27	27	27
	T_{out} (^{0}C)	28	29	30	29.5
	Q (KJ)	126	252	378	315
	Tgain(^{0}C)	1	2	3	2.5
Week 3	T_{in} (^{0}C)	25	25	25	25
	T_{out} (^{0}C)	26	28	31	29.5
	Q (KJ)	126	378	756	567
	Tgain(^{0}C)	1	3	6	4.5
Week 4	T_{in} (^{0}C)	29	29	29	29
	T_{out} (^{0}C)	30	32	40	35
	Q (KJ)	126	378	1386	756
	Tgain(^{0}C)	1	3	11	6

Where

T_{in} (^{0}C) is Average Temperature of cold water, T_{in} (^{0}C)

T_{out} (^{0}C) is Average Temperature of hot water, T_{out} (^{0}C)

Tgain(^{0}C) is Average Temperature gain of water, T_{out} (^{0}C)

Q(KJ) is Average Heat absorbed, Q (KJ)

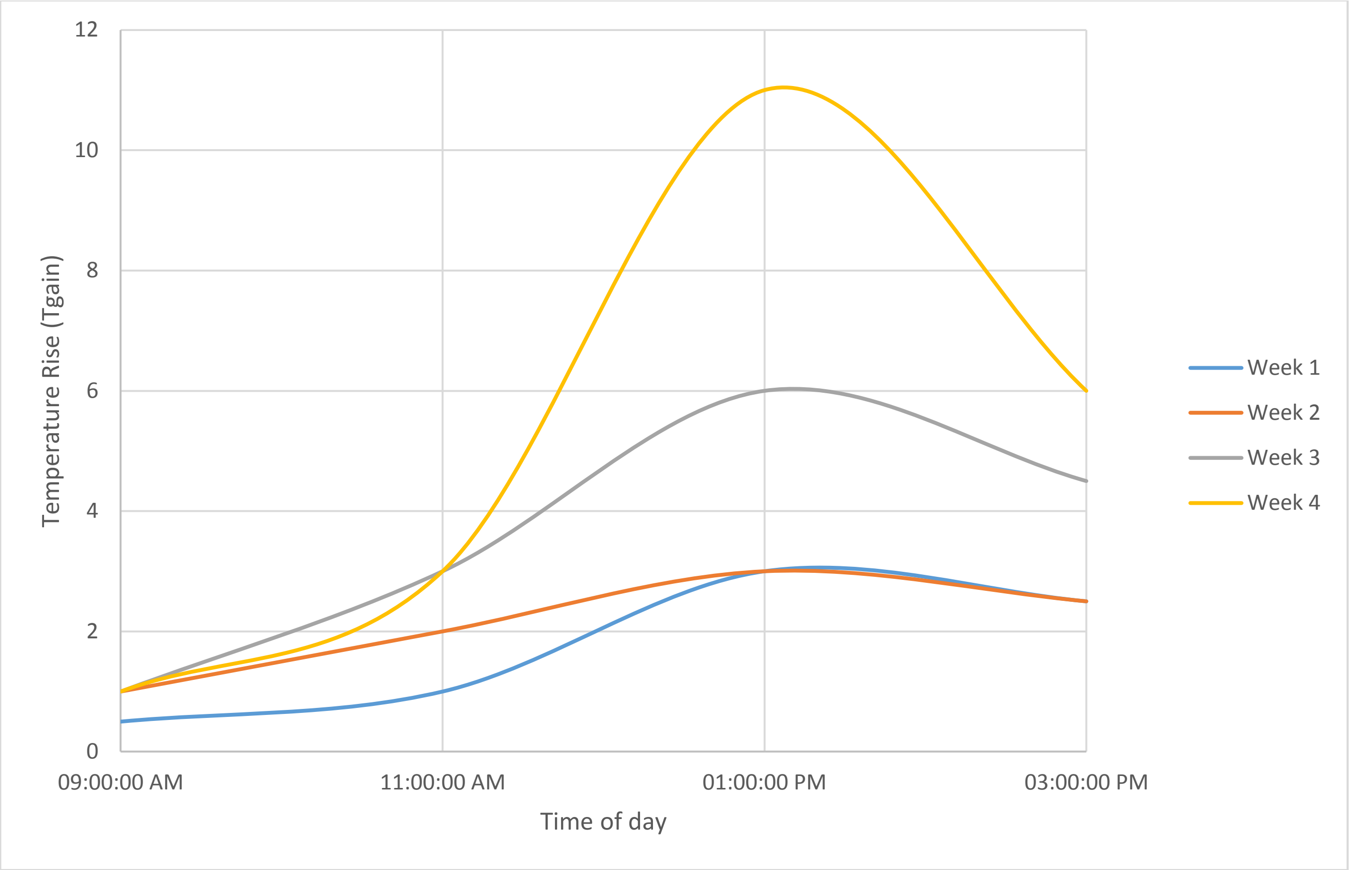

Figure 2: Average Temperature gain of water against Time of the day in June, 2017

The various plots of average temperature gain of hot water against time of the day shows an increase in average temperature gain of hot water obtained up till a peak accompanied by a drop in average temperature of the hot water. The peak average temperature rise occurred at about 1:00:00 PM. The average temperature of hot water and heat absorbed increased from 26.5^{0}C and 63KJ at 9:00 am up till peak of 29^{0}C and 378KJ at 1.00 pm and dropped to 28.5^{0}C and 315KJ at 3.00 pm through week 1 of June, 2017. Through week 2, the average temperature of hot water and heat absorbed increased from 28^{0}C and 126KJ at 9:00 am up till peak of 30^{0}C and 378KJ at 1.00 pm and dropped to 29.5^{0}C and 315KJ at 3.00p.m. At week 3, the average temperature of hot water and heat absorbed increased from 26^{0}C and 126KJ at 9:00 am up till peak of 31^{0}C and 756KJ at 1.00 pm and dropped to 29.5^{0}Cand 567KJ at 3.00p.m. Meanwhile through week 4, the average temperature of hot water and heat absorbed increased from 30^{0}C and 126KJ at 9.00 am up till peak of 40^{0}C and 1386KJ at 1.00 pm and dropped to 35^{0}C and 756KJ at 3.00p.m. It is important to note that the test was carried out during rainy season with frequent occurrence of rainfall, we were unable to measure the solar radiation during the test period because of certain constraints. Hence the instantaneous efficiency could not be calculated.

4.0 CONCLUSION

The following conclusions were dawned from the analysis carried out in this study:

i. Results of one month of testing was recorded, and the weekly average was evaluated analyzed and compared to obtain the average peak temperature of 32.5^{0}C for heating water during the period of testing (June, 2017).

ii. The results from test conducted showed that within a period of 6 hours, between 9.00am to about 3.00pm, a maximum average weekly temperature of 40^{0}C was obtained on Week 4.

iii. Solar thermal heating is a green and cheap source of energy which promises to answer energy needs in the near future.

iv. From the test results and analysis, it is obvious that the use of solar water heater is a green and cost effective way of heating water.

v. This solar water heater can find its use in homes for domestic use and commercial applications. Objectively, the solar water heater cannot be the only sustainable heater in a house because while very good, its efficiency can vary depending on the amount of solar energy available on a given day.

DOI: 10.31695/IJASRE.2019.33634

REFERENCES

1. Kishor, N., Das, M.K., Narain, A., and Ranjan, V.P. (2010) Fuzzy model representation of thermosyphon solar water heating system, Solar Energy, 84 (6) 948-955.
2. Samson, A.A. (2013) Performance of Solar Water Heater in Akure, Nigeria. Journal of Energy Technologies and Policy, 3(6), 1-8.
3. Sambo A.S (2009) Strategic Development in Renewable Energy in Nigeria. International Association for Energy Economics. 3, 15-19.
4. Ilenikhena P.A and Ezemonye L (2010) Solar Energy Application in Nigeria. Wec Montreal 2010: Paper No. 135 Revised, 1-13.
5. Karekezi, S. and Ranja, T. (1997) Renewable Energy Technologies in Africa, London, Zed Books Ltd, ISBN: 9781856490900.
6. Soteris A.K. (2004) Solar thermal collectors and applications. Progress in Energy and Combustion Science, 30(3), 231-295.
7. Heinemann, A, (2015) Solar Collector PA Technology. [Online]
   available at: https://energypedia.info/wiki/Solar_Collectors_(PA_Technology)
8. Nosa, A. O., Ikponmwosa, O.and Julius, J. (2013) Design and Construction of a Solar Water Heater Based on theThermosyphon Principle. Journal of Fundamentals of Renewable Energy and Applications, 3, 1-8.

DOI: 10.31695/IJASRE.2019.33634