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Design and Construction of a Domestic Portable Solar Water Heater

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ABSTRACT
The technology of solar water heating system consists of a collector plate to collect solar energy with an insulated storage tank to store hot water which can be used for domestic, industrial and small institutional purposes. The design and construction of solar water heating will serve as a substitute to the use of an electric heater for producing steam. Due to the epileptic power supply in Nigeria, other energy sources are being sought. This article presents the design and fabrication of a domestic portable solar water heater. The solar water heater was well constructed using available materials. The choice of materials for the components was made based on availability, cost and durability. The system was then constructed using the available materials. A glass with plain surface was used as a collector plate and an aluminium sheet metal painted black was used as an absorber plate. A flow channel pipes attached to the absorber plate as fluid carrying tubes were also designed. The solar energy incident on the coated absorber plate transfers the heat to the fluid carrying pipes underneath the absorber plate placed in an insulated casing with a transparent glass cover having a cold and a hot water tank integrated in the system. The water flowing through the channel pipes gets heated and flows into an insulated storage tank by the principle of thermosyphon system. When tested, an average flow rate of 0.2 litres /minutes was recorded. The system was tested for 5 days, the first two days of testing were during the raining season and the last three days within the dry season. From the entire testing during the raining season, the average inlet temperature recorded was 44.30^0C. For the entire days of testing during the dry season, the average outlet temperature recorded was 70 ^{0}C. The difference in the average outlet temperature recorded indicate that the solar heater performs better during the sunny days when the solar radiation is at its peak. The average solar radiation recorded was 7.50 kW/m^2 on the last day of testing. A total amount of 60 litres of hot water was harnessed which was in excess of hot water needed at home for domestic uses.

I. INTRODUCTION

Recently, because of the epileptic nature of power supply in the country solar energy systems have gained more recognition because they can provide energy at a low long-term cost and minimal environmental damage. Scientists have developed several techniques for harnessing solar energy; these techniques include applications for space heating, water heating, electricity power generation etc. Solar energy is being used for various applications which include power generation, space heating as well as water heating system for domestic and industrial use (Ebubechukwu, 2017). The sun's energy is transmitted by means of electromagnetic radiation from the sun to the earth but will have to be changed into heat energy by means of a device before it can be used for heating. Solar water heating (SWH) process involves the use of the sun's energy to heat water using thermal collector. It involves various technologies that are used in the whole wide world (Atia, 2012).

A Solar water heater is also known as 'solar thermal system'. This device is used for energy dependence as most of our energy is generated from the burning of fossil fuels because of which wide array of environmental issues occur. So, why risk our environment when we can use the sun's energy which freely falls on Earth?

To utilize solar energy, simple equipment is required to capture the heat of the sun. Solar water systems capture this free energy to heat the water. The heated water can be used for a plethora of purposes such as bathing, cleaning, washing etc. Installing solar water heater provides unlimited clean energy and reduces electricity costs (Barry, 2018).

Solar energy is generated by the fusion reaction of hydrogen atoms in the sun. This fusion reaction results in the release of high-energy particles called gamma rays. Gamma rays are transmitted as electromagnetic radiation to the Earth, which is at about 160 million kilometres from the sun. Electromagnetic radiation comes in three forms: infrared rays, visible light, and ultraviolet rays. Solar energy reaching the Earth's surface can be harnessed directly by using photovoltaics (solar cells) and solar concentrators. Photovoltaics are used for electricity generation, while solar concentrators are used as a source of thermal energy (Bestplumbers, 2010). The utilization of solar energy collectors (concentrators) to transform radiation into heat energy is the basis of the solar water heating technology. A simple solar water heater consists of a collector, a tank, and the flow channel through which the working fluid is transported.

Solar energy is the most abundant continuing source of energy available to the human race. Solar energy is not being used as primary sources of fuel energy but a large research and development effort has being underway to develop economical systems to harness solar energy as a major source of energy particularly for the heating and cooling of buildings.

Over the years solar energy has been put to several uses ranging from drying of cloth and agricultural product to sun tanning the body and of course for food preservation. Other areas of solar energy use is air conditioning for cooling and heating of a building for human comfort using absorption cooling system (Joseph & Sherry, 2018). Other area of uses of solar energy is solar cooler, warming pools, operating engine pumps, solar furnace and generating of electricity.

The solar water heating systems are used to produce hot water for most periods of the year but in the raining season where there may not be enough sunshine to produce the desired heat for hot water, a gas or electric booster is incorporated to heat up the water (Gupta, 2019). Solar water heaters which are suitable for hot climate are simpler and cheaper to design and are considered a suitable technology for these places. Heating of water makes use of a greater part of the energy in many residential and commercial homes as it is estimated that about 18% of energy is used in heating water in residential homes and 4% in commercial buildings. Using solar energy to heat water instead of electricity or gas can meet up to 75% of the hot water needed at homes without any environmental pollution (Gong & Sumathy, 2016). Solar water heaters for residential and small institutional purposes can be grouped into two types namely passive which sometimes refers to as "compact" and active which also refers to as "pumped" system (Ebubechukwu, 2017). These two types of heaters can include an auxiliary energy source such as electric heating element or gas which is brought into use when the water temperature in the tank falls below a minimum temperature level, which ensures that there is always hot water available all year round. Also, the use of wood- stove chimney as a backup heat for solar water heating system can also enable hot water system to operate throughout the year including cooler regions without the use of electricity (Adefarati, 2019 & Lilian, 2018).

A Flat Plate Collector is a heat exchanger that converts the radiant solar energy from the sun into heat energy using the well known greenhouse effect. It collects, or captures, solar energy and uses that energy to heat water in the home for bathing, washing and heating, and can even be used to heat outdoor swimming pools and hot tubs (Liji, 2019). For most residential and small commercial hot water applications, the solar flat plate collector tends to be more cost effective due to their simple design, low cost, and relatively easier installation compared to other forms of hot water heating systems. Also, solar flat plate collectors are more than capable of delivering the necessary quantity of hot water at the required temperature.

The flat plate collectors' forms the heat of any solar energy collection system designed for operation in the low temperature range, from ambient to 60 or the medium temperature, form ambient to 100. A well engineered flat plate collector is delivers heat at a relatively low cost for a long duration. The flat plat collector is basically a heat exchanger which transfer the radiant energy of the incident sunlight to the sensible heat of a working fluid-liquid or air (Michaelides, 2011). Flat plate collectors is used to convert at much solar radiation as possible into heat at the highest attainable temperature with the lowest possible investment in material and labour.

Flat plate collector have the following advantage over other types of solar energy collectors:

(i) Absorb direct, diffuse and reflected components o solar radiation,
(ii) Are fixed in tilt and orientation and thus, there is no needed of tracking the Sun,
(iii) Are easy to make and are low in cost,
(iv) Have comparatively low maintenance cost and Long lie, and
(v) Operate at comparatively high efficiency

A solar flat plate collector typically consists of a large heat absorbing plate, usually a

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large sheet of copper or aluminum as they are both good conductors of heat, which is painted and chemically etched black to absorb as much solar radiation as possible for maximum efficiency. This blackened heat absorbing surface has several parallel copper pipes or tubes called risers, running length ways across the plates which contain the heat transfer fluid, typically water (Ksenya, 2011). These copper pipes are bonded, soldered or brazed directly to the absorber plate to ensure maximum surface contact and heat transfer. Sunlight heats the absorbing surface which increases in temperature. As the plate gets hotter this heat is conducted through the risers and absorbed by the fluid flowing inside the copper pipes which is then used by the household.

The pipes and absorber plate are enclosed in an insulated metal or wooden box with a sheet of glazing material, either glass or plastic on the front to protect the enclosed absorber plate and create an insulating air space (Witmer, 2017). This glazing material does not absorb the suns thermal energy to any significant extent and therefore most of the incoming radiation is received by the blackened absorber.

The air gap between the plate and glazing material traps this heat preventing it from escaping back into the atmosphere. As the absorber plate warms up, it transfers heat to the fluid within the collector but it also loses heat to its surroundings (USDE, 2012). To minimize this loss of heat, the bottom and sides of a flat plate collector are insulated with high temperature rigid foam or aluminium foil insulation as show

The working principle of solar water heater is very simple. The device has collectors which absorb the radiations of sun and converts it into heat. Then, with the help of circulating pumps, this heat is passed to a water tank (Zeghib, 2011).

Thermal regulators trigger this exchange only when the collector is hotter than the water inside the tank. In this process, the hot water moves upwards due to its low density and due to gravity head, the cold water with higher density moves down from the water tank.

Generally, collectors are arranged in a series-parallel combination. This helps to get a huge quantity of hot water. At midday, during the summer season, the efficiency of these collectors is at its highest. In addition, the solar water system works great in other seasons as well (Osinowo, 2015).

When the sunlight is insufficient, the water in the tanks is pre-heated and then a backup system brings the water to the needed temperature. This way, the solar water heater working is continuous and generates hot water throughout the year.

II. MATERIALS AND METHODS

The following were the design parameters used in the design of the water heating system.

Construction of Solar Water Heater

Construction of solar water heater is very simple. The important parts of a solar water heater include a solar collector, heat transfer system, the heat transfer fluid, storage tank, pressure valve, piping, etc.

Solar Collector: This is the part of the solar heater which helps to trap the sun’s energy and convert it into heat. Generally, it consists of a metal plate which is black in color and helps to absorb maximum heat. There are pipes below this plate which contain the fluid that gets heated. All these are then connected to the metal plate. The fluid runs through these pipes and gets heated.

Storage Tank: The storage tank may or may not have the insulation. This helps in storage of water heated by heat transfer process. It has an inlet for the cold water at its base and the outlet for the heated water. There are pipes below this plate which contain the fluid that gets heated. All these are then connected to the metal plate. The heat transfer fluid runs through these pipes and gets heated. This fluid then transfers the heat to the water. The tank houses the heat transfer system.

Figure 1: Storage tank

Heat Transfer System: This system has the tubing which carries the heat transfer fluid. This fluid flows through the solar collector and gets heated up. The heated fluid then flows through the pipes to the heat transfer system within the storage tank.

Flat-plate Collector

The flat-plate collector has various components with different functions, hence the materials used for the various components are based on their different functions.

The Absorber Plate

The absorber plate’s main function is to absorb the

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solar radiation incident on the flat-plate collector. Copper, mild steel and aluminium all have high thermal conductivity and absorptivity, but aluminium is selected due to it being lighter than mild steel and its cost being relatively lower than that of copper. It is also corrosion resistant, ductile and a good reflector of visible light and heat

Absorber Plate Coating

Coating the absorber plate is important as it increases the amount of the incident solar radiation absorbed by the plate. Absorber plates are usually coated with black paint, they can also be pre-treated to ensure good adhesion with the paint. Selective coatings reduce the heat loss from the absorber plate, they are highly effective in absorbing solar radiation but do not emit thermal radiation at a high level.

Figure 2: Painted absorber plate and pipe

The Collector Flow Channel

For the piping system tubes, copper is selected because it is tough, and does not fail easily under tension or compressive stress, this makes copper suitable for tube forming. The tubes are attached to the absorber plate by welding, fastening or tight fitting the tubes into shaped sheet fins of the absorber plate. The method used was fastening the tubes to the absorber plate with bolts.

Transparent Cover

The requirements for the transparent cover are that it should have low reflectance, low absorbance, and high transmittance. The material that fits this requirement is glass; it transmits a high amount of the solar radiation incident on the collector and suppresses the convective and relative losses from the top of the solar collector plate. Tempered glass with low iron content is used in many solar collectors due to its strength, safety, and higher collector efficiency. It is highly efficient and also has a higher mechanical strength compared to common glass was used due to the expensive cost of tempered glass.

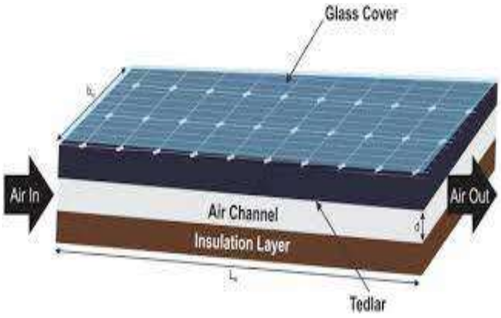

Figure 3: Glass installed on collector frame

Collector Casing

Mild steel was used for the collector casing; this is due to it being cheap and light. The collector frame holds the absorber plate, piping system and the transparent cover. Mild steel also lasts long when exposed to environmental conditions.

Collector Casing Insulation

Styrofoam of 25 mm thickness was used to insulate the bottom and sides of the collector. The Styrofoam was cut into the required sizes and fitted into the collector casing. It is cheap, readily available and has good insulation properties

Working Principle of the Solar Water Heater

Solar Water Heater

The heat transfer system within the storage tank helps to heat the cooler water which is present at the base of the tank. The heat transfer process takes place and the water in the tank gets heated. This heated water moves upward in the tank and is ready for use. Fresh cool water enters the tank through the cold water inlet at the base.

Heat Transfer System

This system has the tubing which carries the heat transfer fluid. This fluid flows through the solar collector and gets heated up. The heated fluid then flows through the pipes to the heat transfer system within the storage tank.

Pressure Valve and Air Vent

The storage tank also has a pressure valve and a vent. The pressure valve regulates the pressure within the tank and helps in air escape, in case of overpressure caused by steam or air.

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III. RESULTS

Results from the experimental set-up of solar water heater are shown below:

Table 1: Readings for the first day of experiments

Time (h)	Ambient Temp. (^{0}C)	Inlet Temp (^{0}C)	Outlet Temp (^{0}C)	Irradiance W/m^2	Efficiency (%)
09:00	24.00	25.00	26.00	465	4.80
10:00	26.00	29.00	30.00	503	1.13
11:00	27.00	29.50	31.50	604	2.10
12:00	27.50	30.00	45.00	726	31.35
13:00	28.00	31.50	55.00	681	65.94

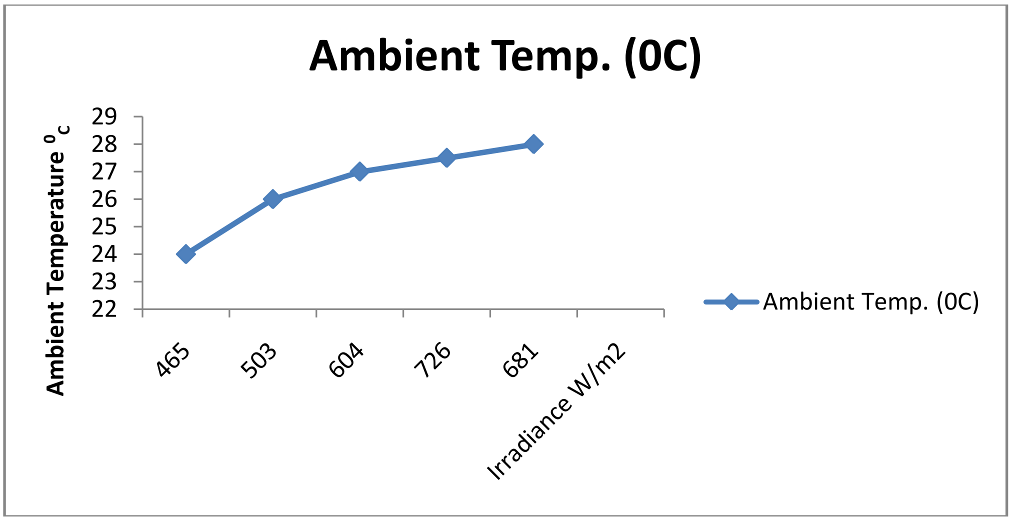

Figure 4: Temperature against irradiance for day one

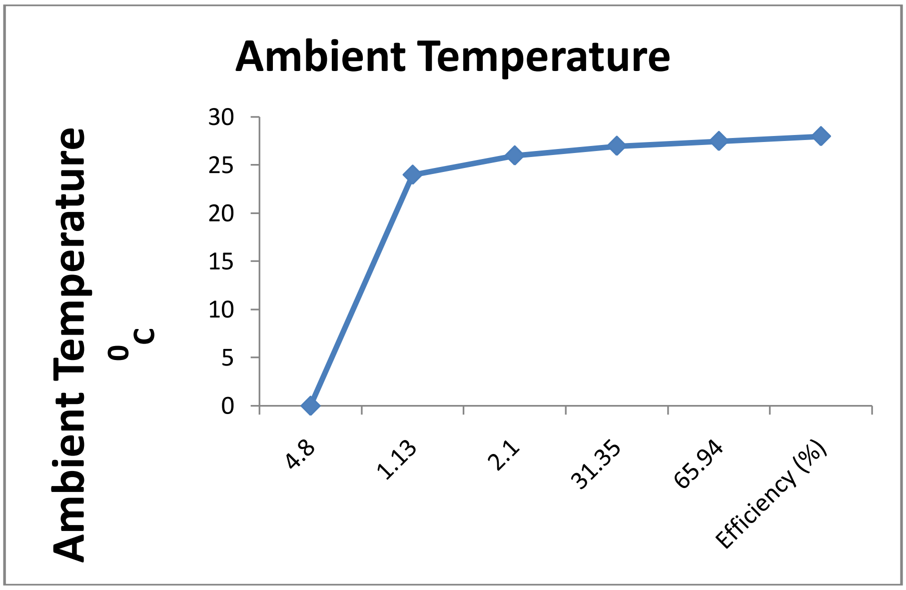

Figure 5: Temperature against efficiency for day one

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From Figure 4, it is seen that the outlet temperature slowly rises for the first few hours, but then increases rapidly from midday till its peak. Figure 5, show that the highest efficiency is observed at the time when the output temperature is at it peaks.

Table 2: Readings for the second day of experiments

Time (h)	Ambient Temp. (^{0}C)	Inlet Temp (^{0}C)	Outlet Temp (^{0}C)	Irradiance W/m^2	Efficiency (%)
10:00	25.00	25.00	27.00	517	4.32
11:00	25.00	25.00	45.80	602	46.55
12:00	26.00	26.00	50.00	614	56.31
13:00	27.00	26.00	51.10	740	40.60
14:00	26.00	29.50	60.00	680	61.70
15:00	26.50	31.00	52.80	491	60.08

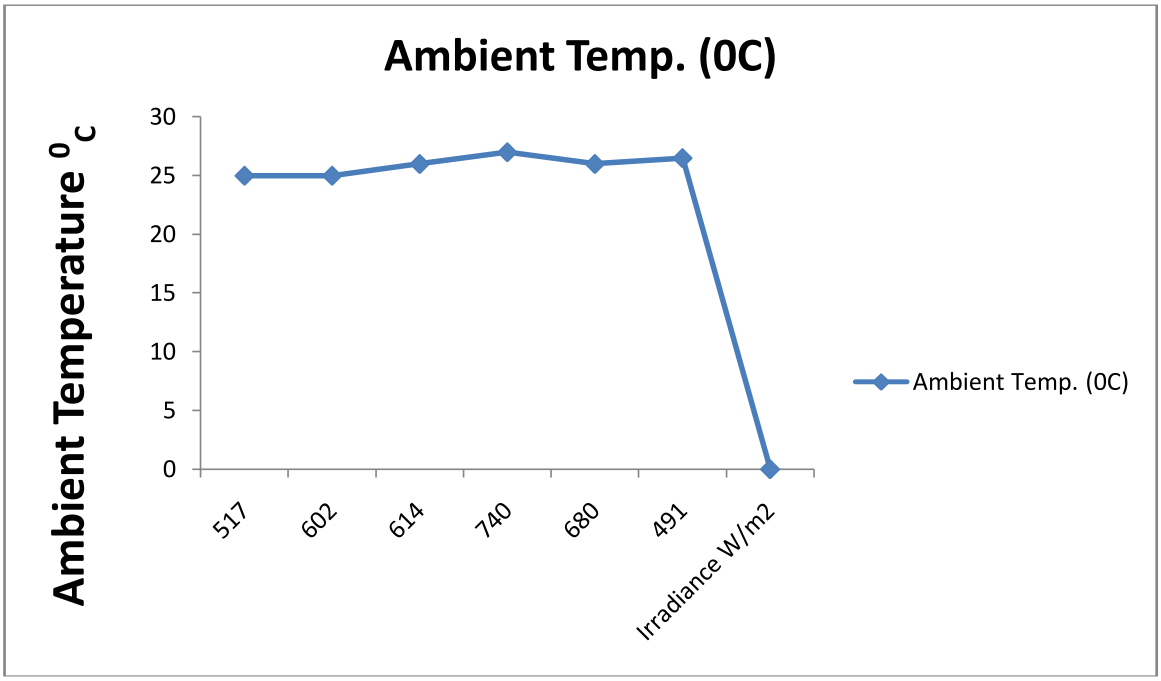

Figure 6: Temperature against irradiance for day two

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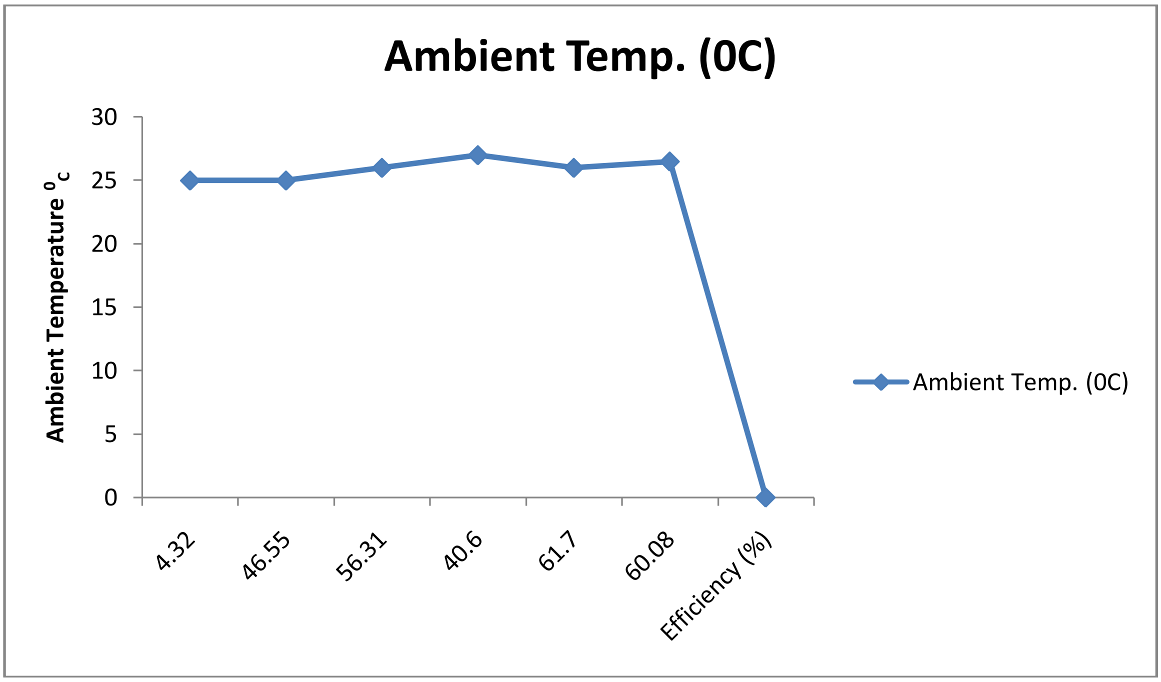

Figure 7: Temperature against efficiency for day two

Figure 6; shows the irradiance peak while the ambient drops a bit. Figure 7; shows that the efficiency of the system has a similar trendline to that of the temperature. The maximum efficiency recorded on day two was lower than the maximum on day one.

Table 3: Readings for the third day of experiments

Time (h)	Ambient Temp. (^{0}C)	Inlet Temp (^{0}C)	Outlet Temp (^{0}C)	Irradiance W/m^2	Efficiency (%)
09:00	24.00	24.50	23.50	369	2.55
10:00	25.00	23.50	40.50	368	55.10
11:00	26.00	24.60	45.40	537	55.50
12:00	27.00	26.30	55.50	617	60.07
13:00	27.50	28.50	52.00	595	50.65

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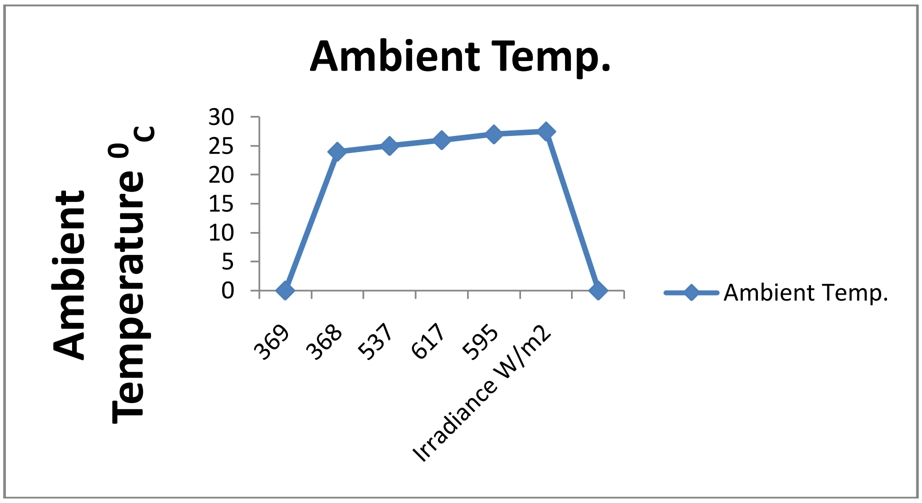

Figure 8: Temperature against irradiance for day three

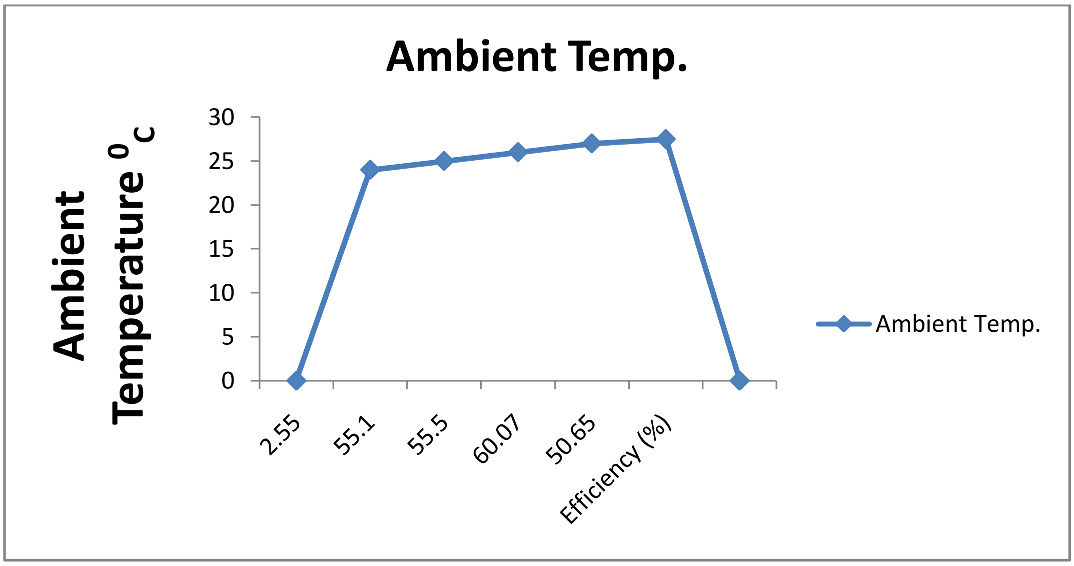

Figure 9: Temperature against efficiency for day three

Unlike the results from the first two days, Figure 8; shows that the irradiance levels peak at the same time as the ambient temperature rises gradually then stays constant. From Figure 9; It is observed that the efficiency dips a bit even as the output temperature keeps rising. The efficiency then rises till its peak.

Table 4: Readings for the fourth day of experiments (28/10/20 readings)

Time (h)	Ambient Temp. (^{0}C)	Inlet Temp (^{0}C)	Outlet Temp (^{0}C)	Irradiance W/m^2	Efficiency (%)
09:00	28.00	27.50	29.50	705	1.57
10:00	29.00	28.60	49.50	808	21.04
11:00	31.00	30.50	75.30	830	58.19
12:00	32.00	34.40	73.50	768	50.17
13:00	33.00	40.70	69.70	631	42.73

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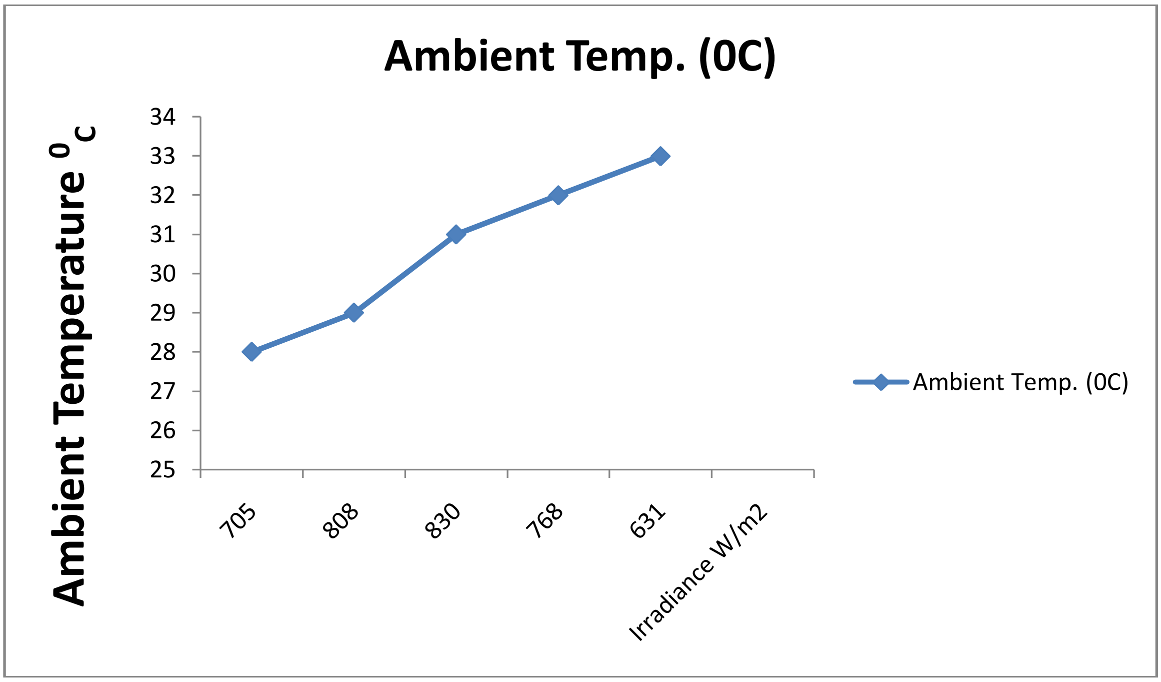

Figure 10: Temperature against irradiance for day four

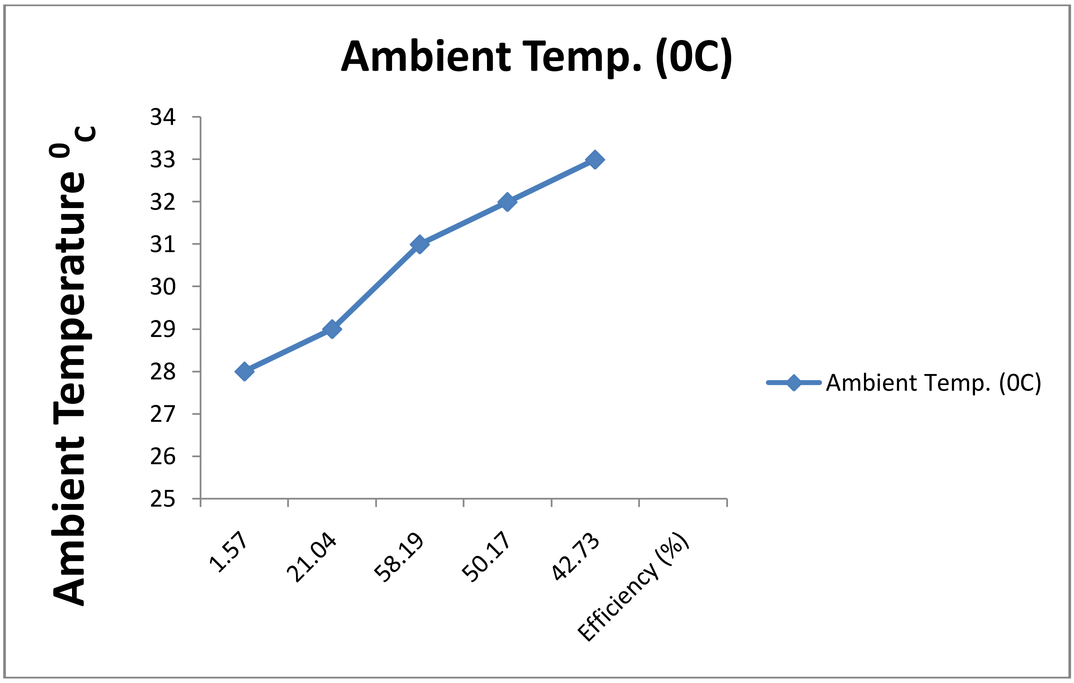

Figure 11: Temperature against efficiency for day four

Figure 10' shows a significant increase in the irradiance levels compared to the first three days of testing. The temperature also peaks at and reached higher values compared to results for the first three days. From Figure 11; it is noticeable that the efficiency ant the outlet temperature have a close relationship as they peak at the same time. They both rise and fall with similar gradients. This is in correlation to the trend observed for day one and three.

Table 4. 5 Readings for the fifth day of experiments (29/10/20 readings)

Time (h)	Ambient Temp. (^{0}C)	Inlet Temp (^{0}C)	Outlet Temp (^{0}C)	Irradiance W/m^2	Efficiency (%)
09:00	28.00	29.50	30.50	724	1.35
10:00	28.00	32.50	52.10	803	18.76
11:00	30.00	35.60	74.00	803	48.45
12:00	31.00	40.40	62.50	723	25.09
13:00	31.50	44.30	59.30	571	18.41

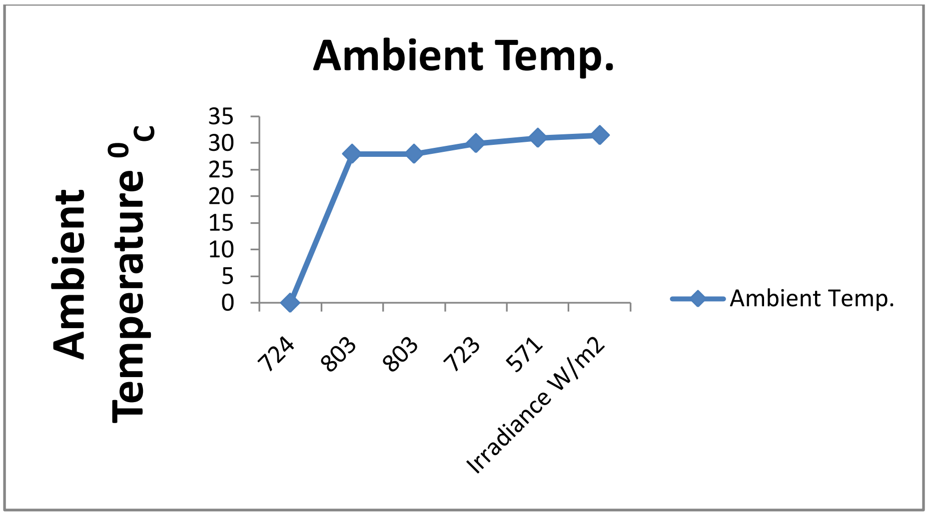

Figure 12: Temperature against irradiance for day five

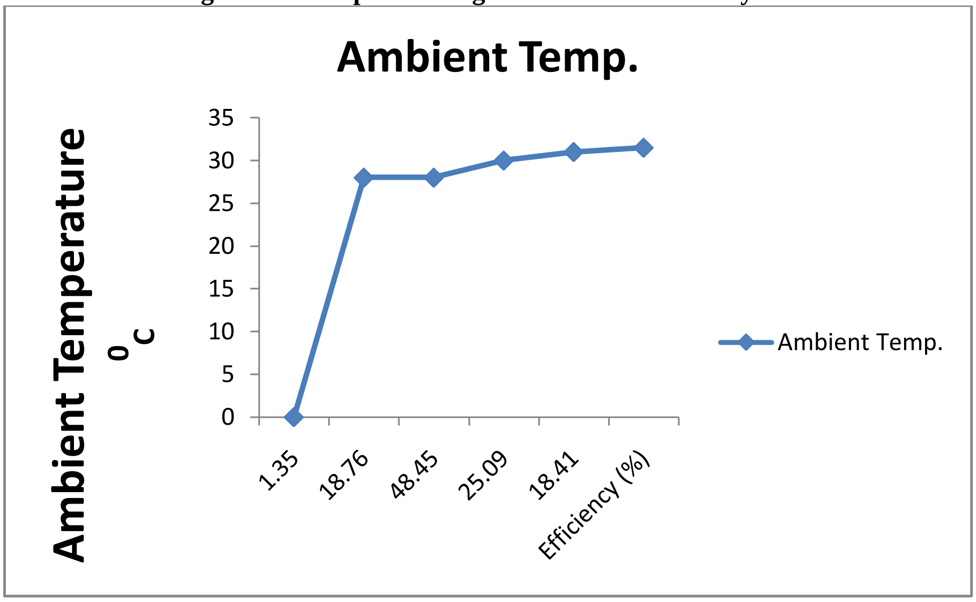

Figure 13: Temperature against efficiency for day five

Figure 13; shows that the irradiance rises between and gradually falls due to temperature difference. The temperature also rises like that of day four. Figure 13; shows that the efficiency and the temperature both peak at the same time and have similar identity. This shows a similar with results obtained from day four.

IV. DISCUSSION OF RESULTS

It is seen from the overall results that that the irradiance levels and the output temperature are closely related. For the entire days of testing during the late raining season, an outlet temperature of 44.30 ^{0}C was the highest temperature observed. However, for the entire days of testing during the dry season, the maximum outlet temperature observed was 75 ^{0}C. This clearly shows that the system performs better during the dry season. The total volume of water heated up was 60 litres. (Ogie, 2013) designed a solar water heater to provide 75 litres of water at 60 ^{0}C daily. From their design, the collector area required was 1.464 m^2. However, they used an area of 2.3m^2 during the construction of their system and obtained a maximum output of 76 ^{0}C. Comparing the two results shows that although (Rikoto, 2015) used a larger collector area, their peak outlet temperature was slightly lower than the peak value obtained in this work. This shows that using a larger collector area would not necessarily improve performance, the irradiance available at the system site also plays a role on system performance.

V. CONCLUSION

In this article, the design and construction of a 60 litres capacity portable solar water heater has been carried out. Using relevant materials, equations to size the major components of the system. The materials for the design were then selected with consideration to the design calculations, market availability and cost of the materials. The system was tested and certified as working material. From the results obtained it was clearly shows that the solar energy heater performs better during the dry season when the irradiance levels are higher.

Recommendations

In order to improve the operational performance of the solar water heater, the following recommendations should be considered.

i. A better and very good insulation material should be used as there was heat loss from the material used.
ii. Since there are almost 30% energy losses to surrounding, the system needs better insulation performance. The price of insulation materials is relatively inexpensive, therefore doubling the thickness of insulation material is recommended.
iii. As a matter of our economic situation, the government of Nigeria and cooperate organizations should partner in order to install this type of heater in the Polytechnics, Universities and Colleges across the country as well as in our hospitals especially the maternity wards where a lot of hot water is used to help reduce the cost of heating water.
iv. Installation of a sensor to determine water level and control flow.
v. Installation of a flow meter to easily get flow rate of working fluid.

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