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Performance Evaluation of an Active Solar Still under Forced Circulation Mode

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Abstract
Water is fundamental to human life on earth for survival and good health. Access to safe water is a major challenge to many communities both urban and rural in Nigeria. As Nigeria's population continues to grow with the social-economic problems already quite visible, communities will continue to be challenged to provide fresh water to meet those needs for all of their people. Growing demands of freshwater resources are creating an urgent need to develop self-sustained systems to meet the demand of fresh water. Among the conventional distillation process, solar distillation process seems to be a suitable solution for resolving this existing demand of fresh water. This is quite true especially in areas where the water table is already contaminated or polluted such as in the artisanal mining areas of Northern Nigeria. The purpose of this work was to design and fabricate a solar water distillation system that can purify the water from various sources. Such sources include water from contaminated wells and boreholes, streams and rivers and even runoff water from plants and domestic buildings. Solar water distillation removes impurities such as salts and heavy metals such as lead, arsenic and mercury as well as eliminates microbiological organisms. A Solar Still has been designed and fabricated because of the portable water and energy challenges of the rural areas in the country. The incoming solar radiation from the sun heats the water, which placed in the basin in impure form, and this water gets evaporated and condensed into pure drinkable water. In this work, a basin types double slope active solar still was designed and fabricated, and a performance evaluation was carried out. To determine the efficiency of the still.

1.0 Introduction
The need for good drinking water is on increase over the years due to importance of good health. Rapid economic growth and climate change have resulted in increasing pressure on quality and quantity of water resources-especially in tropical and developing countries. There is often enough water available, but it is salty, brackish and need technique to make it safe to drink. Most people

in Nigeria have no access to good drinking water. This is particularly so for areas where artisanal mining is rampant.

During many of the processes used by artisanal miners, toxic materials are released into the environment, posing large health risk to the miners, their families and surrounding communities. For instance, gold mining operations are particularly dangerous, as they often use mercury amalgamation process to extract gold from ores. Furthermore, these materials find their way into the water table poisoning wells and other water sources. Remediation is very expensive for most State governments because of the cost involved.

Heavy metals are dangerous because they tend to bioaccumulate. Bioaccumulation means an increase in the concentration of a chemical in a biological organism over time, compared to the chemical's concentration in the environment. Heavy metal toxicity can result in damaged or reduced mental and central nervous function, lower energy levels, and damage to blood composition, lungs, kidneys, liver, and other vital organs. Long-term exposure may result in slowly progressing physical, muscular, and neurological degenerative processes that mimic Alzheimer's disease, Parkinson's disease, muscular dystrophy, and multiple sclerosis. Allergies are not uncommon and repeated long-term contact with some metals or their compounds may even cause cancer (International Occupational Safety and Health Information Centre, 1999). Lead and mercury exact their most devastating toll on the developing brain (http://www.purewaterservices. co.nz/contaminant s/other-contaminants-issues/heavy-metals):

a. Children exposed to lead at a young age are more likely to suffer from shorter attention spans and are less able to read and learn than their peers.
b. Children with above-average mercury exposures have learning difficulties.
c. Recent studies also suggest that arsenic can harm the developing brain.
d. Many other health effects of these metals are well-known.

Emerging distillation technology using renewable energy is viewed as a feasible alternative to supply water as it can be cost effective but also has potential to transform the lives of people living in small communities in remote and rural areas.

Various researchers have been carried out research works on design, fabrication methods, and performance analysis of solar distillation. Kabeel and El-Agouz (2011) investigated an active system of conventional solar still integrated with a flat plate collector under thermo siphon mode and found that up to 33% increase in the distillate yield when the water is preheated in the collector. An air-blown, multiple effect solar still with heat energy recycle to increase in yield has been proposed by Mink et al. (1998). Kwatra (1996) simulated the relationship between the evaporation area and distillate yield and shows that an enlarged evaporation area increases the yield. Khalifa *et al*. (1999) studied the effect of feed water preheating on single and double slope solar stills and concluded that yield output and efficiency of the solar still has been increased by preheating. Sethi and Dwivedi (2013) developed the convective mass transfer relation for double condensing chamber solar still. In relation Nu = C(GrPr)n, the values of C and n were determined using regression analysis for different temperature ranges and found that the values of C and n proposed by Dunkle (1961) are valid only for lower temperature ranges, however for higher temperature ranges the values of C and n change. Rubio et al. evaluated the distillate yield for a double-slope solar still under controlled conditions for basin water and collector temperatures within typical operating ranges and propose a new empirical model for estimating mass flow rates in single slope solar stills. Nafey *et al.* (2001) has studied the various parameters affecting solar still performance and developed an equation relating the dependent and independent variables to predict the single-slope solar still productivity.

Thermal models to establish the energy balance equations of active and passive solar still have been developed by Tripathi and Tiwari (2005) and validated the theoretical results with the experimental results. Abu-Hijleh *et al.* (2003) studied the effects of sponge cube and showed that the daily production of solar still can be greatly improved. Radhwan (2005) studied the performance of a stepped solar still with built-in latent heat storage and conclude that efficiency and fresh water production rate increased. El-Sebaii *et al*. (2009) studied an analytical solution of the energy-balance equations for the thermal performance of a triple-basin solar still and found that productivity of the bottom basin is higher than the productivity of the upper basins during the daytime. Sow et al. have carried out the exergy analysis for distiller driven by solar energy and reported that the exergetic efficiencies less than 4% for single effect system, 17-20% for double effect system and 19-26% for triple effect solar distiller system. Stephen *et al.* (2012) fabricated plastic solar still and studied the effect of water depth on mass and heat transfer and found that distillate output of 2.1 L/m^2/day, at water depth of0.02m in still basin, could be achieved. Lindblom (2010) have shown that the efficiency of single slope solar still using the black granite gravel reaches up to 52%maximum which is 8% higher than the conventional single slope solar still. Ahsan and Fukuhara (2009, 2010) proposed a new mass and heat transfer model of a tubular solar still incorporating various mass and heat transfer coefficient taking account of the humid air properties inside the still.

Stephen *et al.* (2012) study the effects of orientation and depth of water in the basin of the still on the productivity of a double slope solar still and compared the same with that of a single slope solar still. The authors have done work on new design of solar collector by replacing the conventional collectors with the GI plate sandwiched collectors and compared the steady state outlet temperature and efficiencies.

2.0 Importance of Solar Stills

It has been established through experimental and mathematical model results that the best performance of solar powered systems is achieved if the high intensity of insulation, minimum wind velocity and full insulation exist. Nigeria climatic conditions meet these criteria.

Growing demands of freshwater resources are creating an urgent need to develop self-sustained system to meet the demand of fresh water. Among the conventional distillation process, solar distillation process seems to be a suitable solution for resolving this existing demand of fresh water. Solar water distillation removes impurities such as salts and heavy metals as well as eliminates microbiological organisms. The water produced by the process can be considered pharmaceutical grade.

In order to tap this seemingly boundless resource (solar energy), the purification of water from polluted wells, crude oil polluted water sources, salty sea water, using solar still should be the most promising process, as this process basically removed impurities such as dirt, microorganisms, crude oil and its related constituents, salt, etc., from these polluted sources to produce purified water. It is one of the most important methods of getting potable water. Besides of being inexhaustible, clean and universally available, the use of solar energy in renewable energy based-solar still, is moreover significantly more economical than the use of fossil fuels (Stephen *et al*., 2012). To rationalize the use of this energy source in water purification, an improved solar still that can produce purified water from various sources has been designed and evaluated. A double solar heat collection system is being proposed. We expect that our configuration will improve the overall efficiency of the still. In addition, all equipment on the fabricated rig will be solar powered making it possible to be installed in rural communities where electric power is unavailable.

In this work, a double slope active solar still under forced circulation mode was designed and fabricated, and distillate output and instantaneous thermal efficiency calculated at different water depths.

3.0 Design View/ (Isometric Sketch)

The isometric, Orthographic Projections and exploded view are shown in Figures 1a to 1f.

4.0 Design Assembly

The Complete Design Assembly is presented in Figure 2.

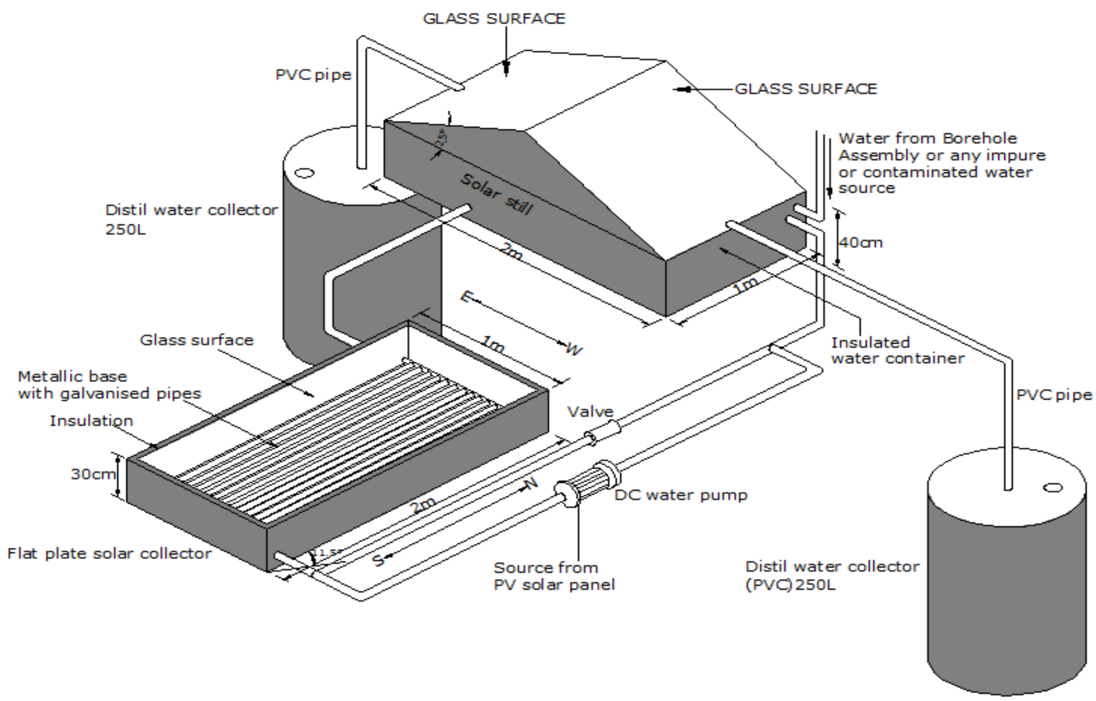


Figure 1a: Isometric Sketch of key components (solar Still and Flat Plat Solar Collector)

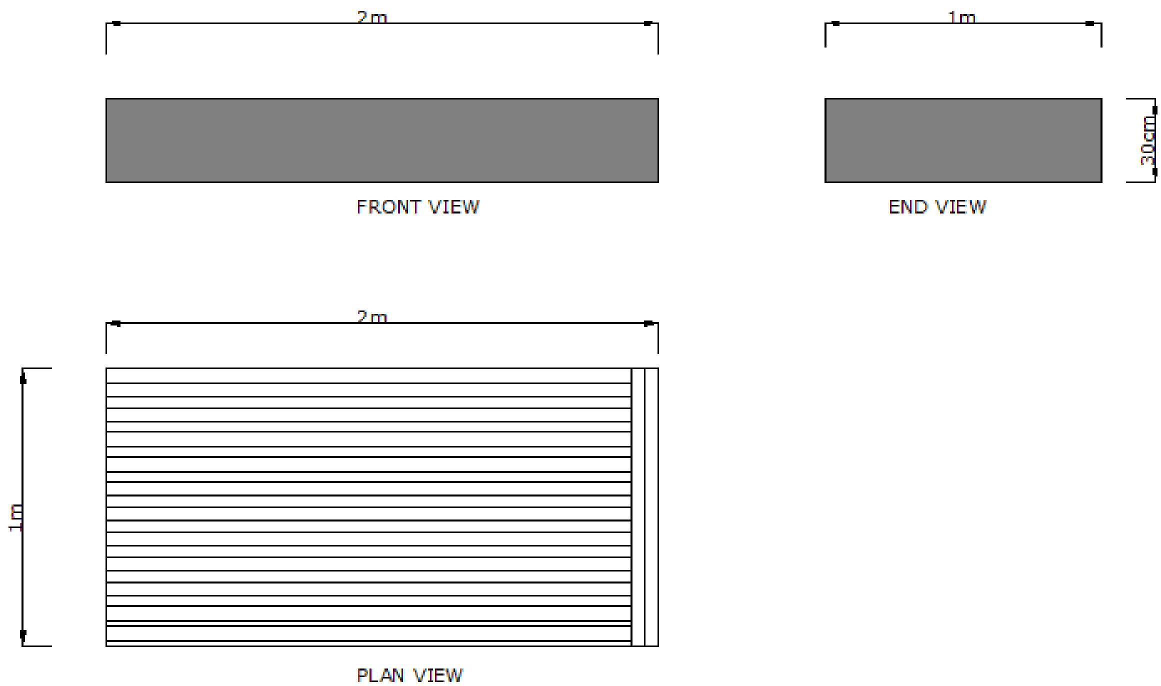


Figure 1b: Orthographic Projection of Solar Collector

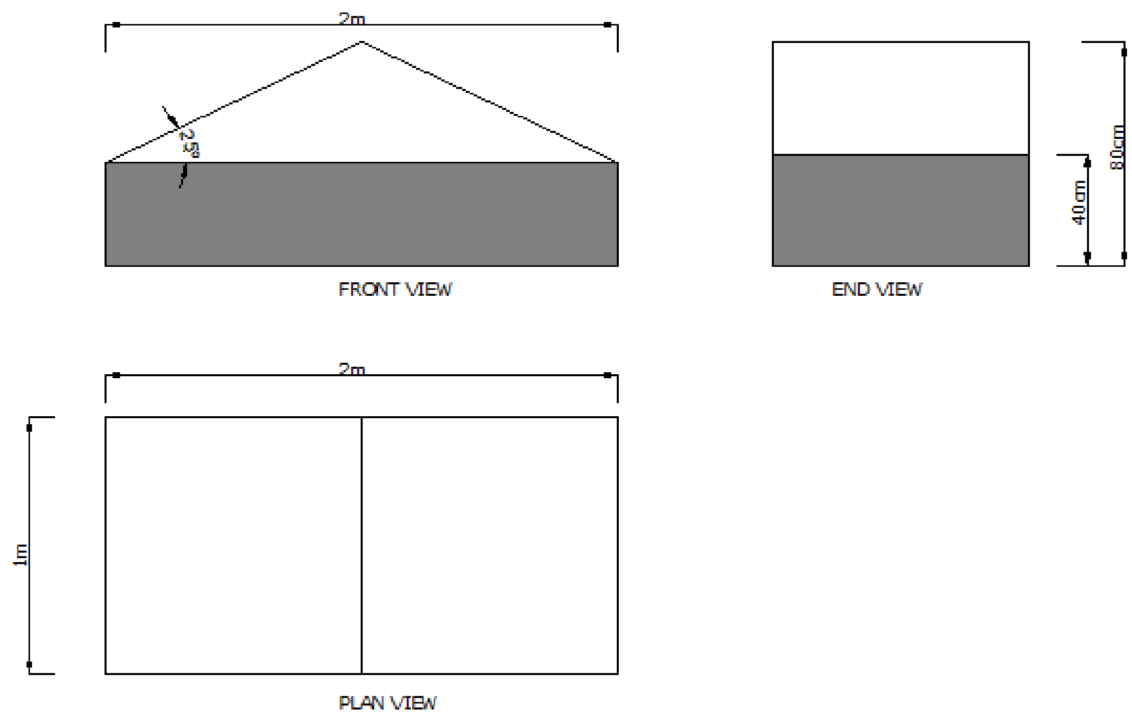


Figure 1c: Orthographic Projection of Solar Still

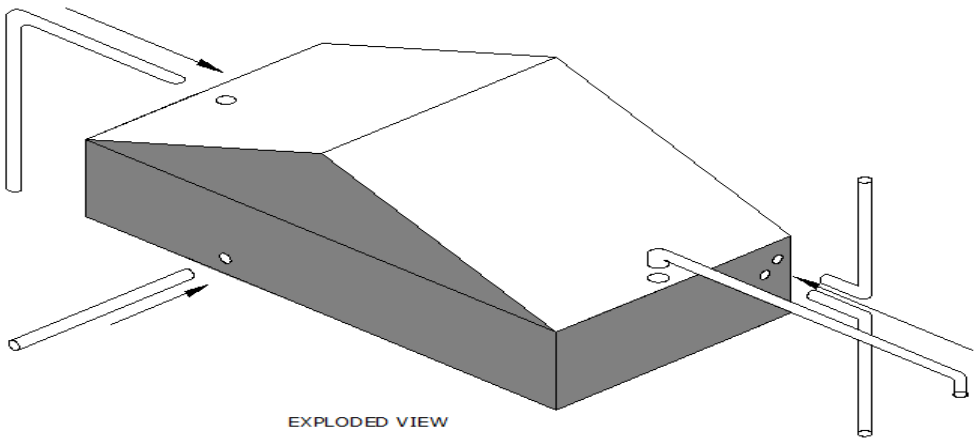


Figure 1e: Exploded Diagram for Solar Still

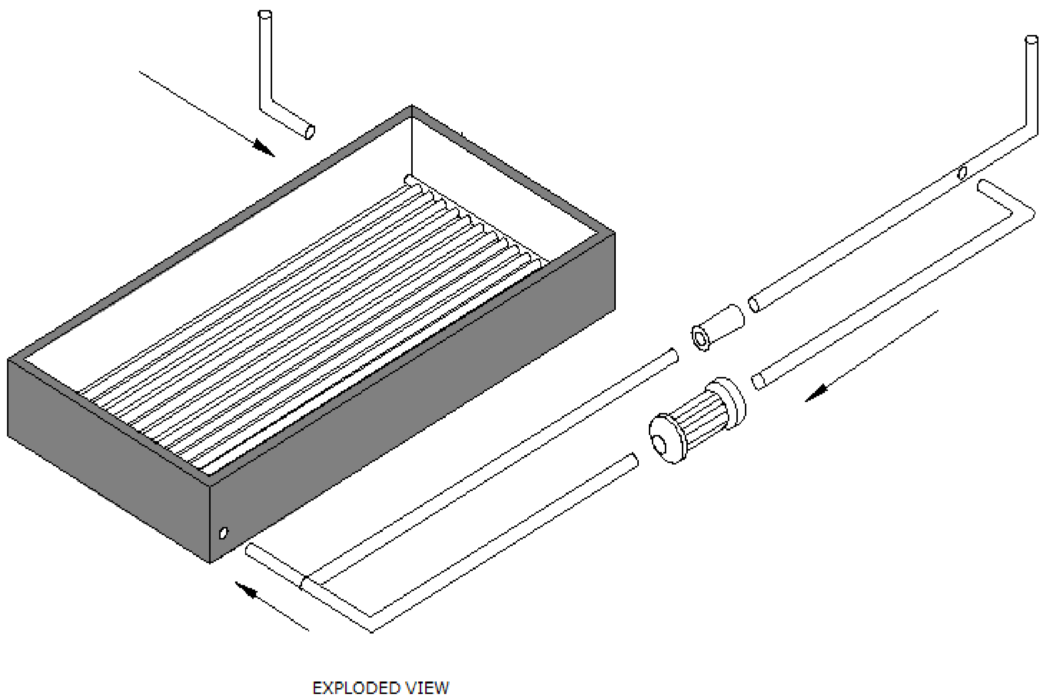


Figure 1f: Exploded Diagram for Solar Collector

5.0 Basic Operation of Solar Still

Water to be purified is poured into the still to reach a set level. The glass cover allows the solar radiation to passes through and it reaches the bottom of the still which is mostly absorbed by the base because the surface is coated with black colour material to increase the sun heat absorption. The water begins to heat up and the moisture content of the air trapped between the water surface and the glass cover. Due to heating water gets evaporated from the basin and condenses on the inside of the cover of the glass. In this process, the impurities that present in the initial water are settled in the base itself and only Condensed water trickles in the inclined glass cover towards downward direction to collection trough and it is stored in the bottle. Every day the basin of the solar still must be cleaned to remove the settled salt contents and impurities. By removing these only, we can absorb more amount of heat energy without wastage.

6.0 Materials and Method of Fabrication

As shown in the schematic diagrams (Figure 1a to 1e), the distillation set-up consisted of four main parts:

i. A solar still without any moving parts. Solar still basin will be made up of a fiber reinforced plastic (FRP) to withstand the harsh conditions produced by water and sunlight. The advantages of FRP over other reinforcing materials such as glass fiber, carbon fiber etc are their specific strength properties, easy availability, light weight, high toughness, non-corrosive nature, low density, good thermal properties, renewability and biodegradability.
ii. A Flat-plate collector which is a metal box with a glass cover (called glazing) on top and a black-colored absorber plate on the bottom. The sides and bottom of the collector will be insulated to minimize heat loss.
iii. A DC water pump powered by solar energy from a solar panel and inverter system.
iv. The distillate water will collect in a plastic channel fixed at the lower end side of both the glass covers. The distillate collected is continuously drained through flexible pipe and stored in dedicated containers placed outside on both sides.

7.0 Measuring Instruments: Measurement of temperature:

Copper-constantan thermocouples were be used to measure water vapor and condensing cover temperature. Thermocouples used in the set-up were properly calibrated with the help of zeal thermometer (standard thermometer). The ambient air temperature will be recorded with the help of a calibrated mercury thermometer.

Measurement of solar radiation: The solar intensity was measured with the help of a calibrated solarimeter, having least count of 20 W/m^2.

Set-up: In active solar still, the flat plate collector is usually coupled with solar still in such a way that the hot water from collector plate enters into the basin of solar still under forced circulation mode. The inlet and outlet connections to the collector plate was taken from the bottom of the basin. A valve was provided in the inlet pipe to control the circulation of water through the collector plate. The collector plate absorbs the solar energy and transfers that energy to water flowing through tubes. The double slope solar still placed in east-west direction and collector plate was inclined at 11.5^o (Latitude for Kaduna) facing south to receive the maximum possible solar radiation.

8.0 Fabricated Equipment

Figures 2a to2d show the pictorial view of the fabricated equipment. Table 1 shows a summary of the materials used in the fabrication.

Table 1: Summary of the Materials Component of the Solar Still Considered

S/N	Component	Material(s)	Properties and Comments
1	Collector/Glazing (Trans- parent)	Plastic Glass	• Low water absorptance • High thermal conductivity • Transparent to short wave radiation (Transmittivity = 0.9) • Low iron content • Can withstand the effect of weather, wind,
2	Basin (Absorber)	Galvanized Iron	• High radiation absorptivity • Stable to corrosion • High thermal conductivity
3	Solar Reflector	Galvanized Iron	• Minimum corrosion problem • High thermal conductivity • High reflectivity • Cheaper and readily available
4	Cover (Casing)	Plywood/iron	• Has uniform strength • Has no cleavage • Very durable even though it is more expensive than hard wood • Stronger, Light weight and cheaper • Good insulator
5	Insulator	Fiber Glass	• Very cheap • Poor conductivity and radiation of heat • Very effective for insulation
6	Sealant	(i) Araldite (ii) Putty	• Can withstand high temperature • Good resistance to organic liquids • Joint bounded with it are difficult to break • Slow curing epoxy • Poor adhesive strength • Soften under high temperature • Cheap and readily available
7	Drain Pipe	PVC	• Stable to corrosion • Not poisonous to water • Cheap and readily available
8	Support Structure	Iron stand	• High tensile strength • Cheap and easily constructed
9	Collection trough	Rubber troughs	• Stable to corrosion • Not poisonous to water

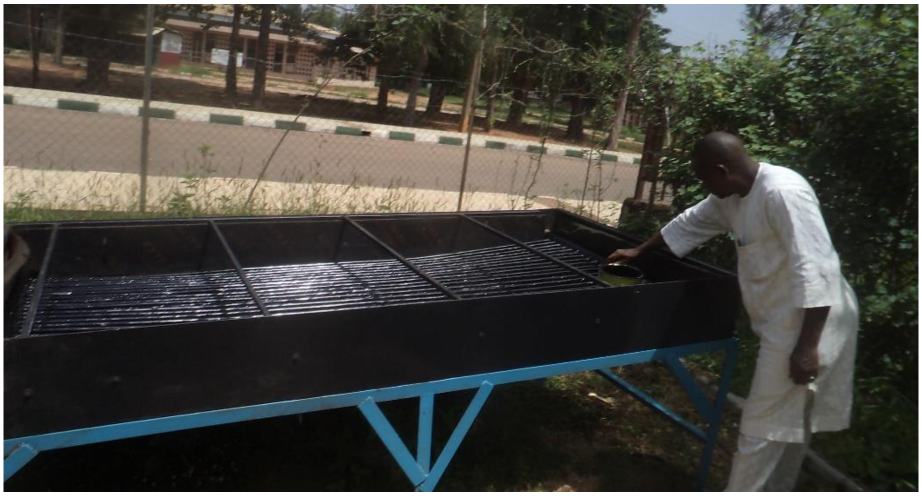


Figure 2a: Pictorial view of Solar Collector before cover is placed on it

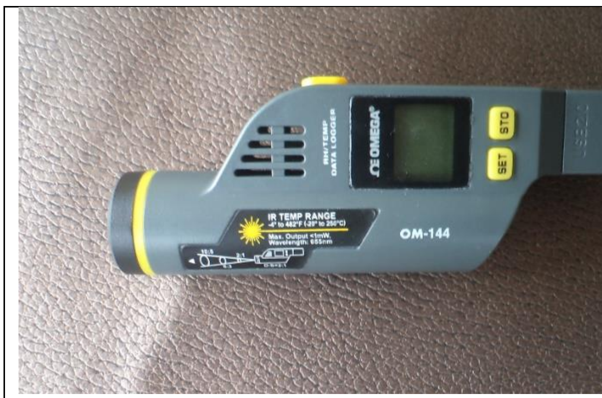
Figure 2b: Pictorial view of Solar Collector after Cover is placed on it

Figure 2c: Pictorial view of Solar Still built to Specification

Figure 2d: Pictorial view of Solar Collector and Solar Still connected together

9.0 Instrumentation

Pictorial views of the instruments and equipment used for various measurements are presented below.

	
Hygrometer/Ambient Temperature Analyser	**Analog and Digital thermocouple readers**
	
Inverter	**Thermocouple coils**

	
Water flow Sensors	**Solarimeter**

9.0 Testing the Fabricated Setup

The following parameters have been be measured every half an hour for a period of 9 hours during each runs conducted. These details are very important parameters necessary for scale up:

i. Ambient Temperatures,
ii. Water temperature from the solar collector
iii. Solar Intensity
iv. Amount of distillate for various times of the day

The data generated during the testing of the fabricated rig is presented on Tables 1 to 3 and Figures 3 to 5.

Table1: Amount of pure distilled Water collected during Interval (litres)

Time	**Day1**	**Day2**	**Day3**	**Day4**	**Day5**	**Day6**	**Day7**	**Average**
9.00-9.30	0.12	0.09	0.11	0.15	0.12	0.08	0.11	
9.30-10.00	0.22	0.18	0.16	0.21	0.21	0.22	0.19	
10.00-10.30	0.29	0.27	0.26	0.23	0.28	0.28	0.26	
10.30-11.00	0.39	0.40	0.39	0.41	0.47	0.46	0.32	
11.00-11.30	0.40	0.45	0.48	0.49	0.55	0.47	0.37	
11.30-12.00	0.46	0.55	0.55	0.64	0.67	0.58	0.56	
12.00-12.30	0.79	0.82	0.80	0.87	0.86	0.91	0.75	
12.30-1.00	0.88	0.91	0.87	0.99	0.96	0.96	0.94	
1.00-1.30	0.98	1.02	1.07	1.14	1.17	1.11	0.94	
1.30-2.00	1.21	1.22	1.18	1.25	1.32	1.31	1.15	
2.00-2.30	1.09	1.19	1.19	1.29	1.25	1.25	1.12	
2.30-3.00	0.99	1.02	1.02	0.92	1.17	1.07	0.94	
3.00-3.30	0.71	0.81	0.81	0.81	0.98	0.90	0.79	
3.30-4.00	0.50	0.60	0.59	0.61	0.73	0.57	0.55	
4.00-4.30	0.34	0.31	0.30	0.32	0.43	0.33	0.27	
4.30-5.00	0.22	0.24	0.24	0.24	0.22	0.29	0.20	
Average Ambient Temperature (ºC)	33.5	30.2	32.3	30.6	29.5	30.2	31.3	**31.1**

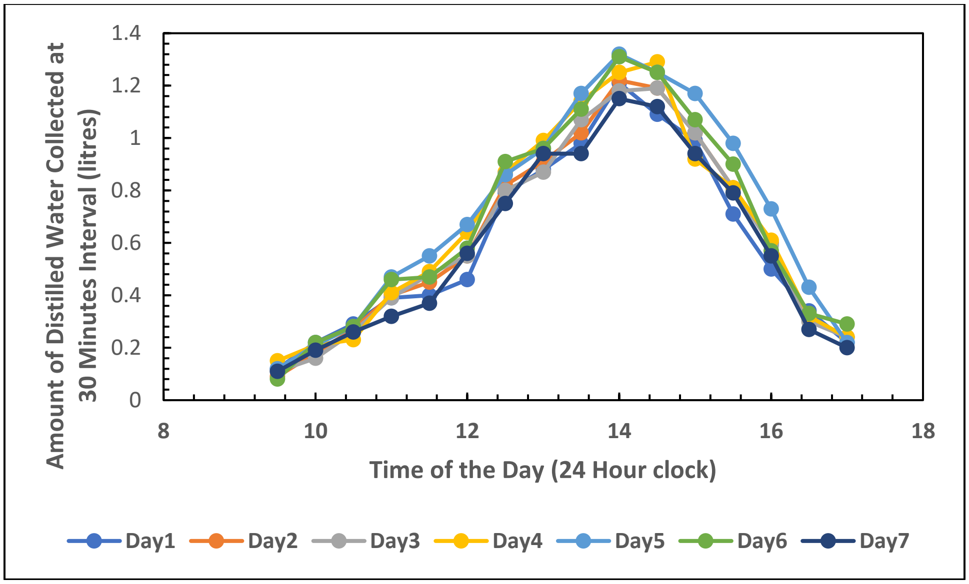


Figure 3: Amount of pure distilled Water collected during Interval (litres) for various times of the day for selected days in October, 2020

Table 2: Water temperature into still from solar collector (°C) for selected days in October, 2020

Time	Day 1	Day 2	Day 3	Day 4	Day 5	Day 6	Day 7	
9.30	32.2	31.09	32.45	35.20	31.91	31.44	32.05	
10.00	37.0	36.79	37.23	42.24	38.11	36.09	38.33	
10.30	40.0	39.62	41.68	44.15	41.05	38.92	41.98	
11.00	51.0	50.88	50.97	57.54	50.77	51.18	51.17	
11.30	57.0	56.75	57.98	64.12	56.78	57.25	58.08	
12.00	60.0	58.68	61.03	67.88	59.55	58.18	62.36	
12.30	68.4	65.90	69.57	74.93	68.33	64.88	68.78	
13.00	70.3	68.75	71.50	77.35	70.88	67.15	73.48	
13.30	78.0	78.28	79.34	86.48	77.98	79.08	79.94	
14.00	73.9	73.27	75.17	83.93	73.50	72.97	78.27	
14.30	65.0	63.57	66.11	74.06	64.55	64.27	62.68	
15.00	62.0	61.64	63.06	66.75	63.34	62.64	64.54	
15.30	58.0	57.72	58.99	65.42	5755	57.02	58.99	
16.00	47.0	45.57	47.80	53.56	47.67	44.47	47.80	
16.30	40.5	40.2	41.19	45.90	40.99	41.22	40.19	
17.00	38.0	37.36	38.65	41.24	37.94	36.16	37.05	

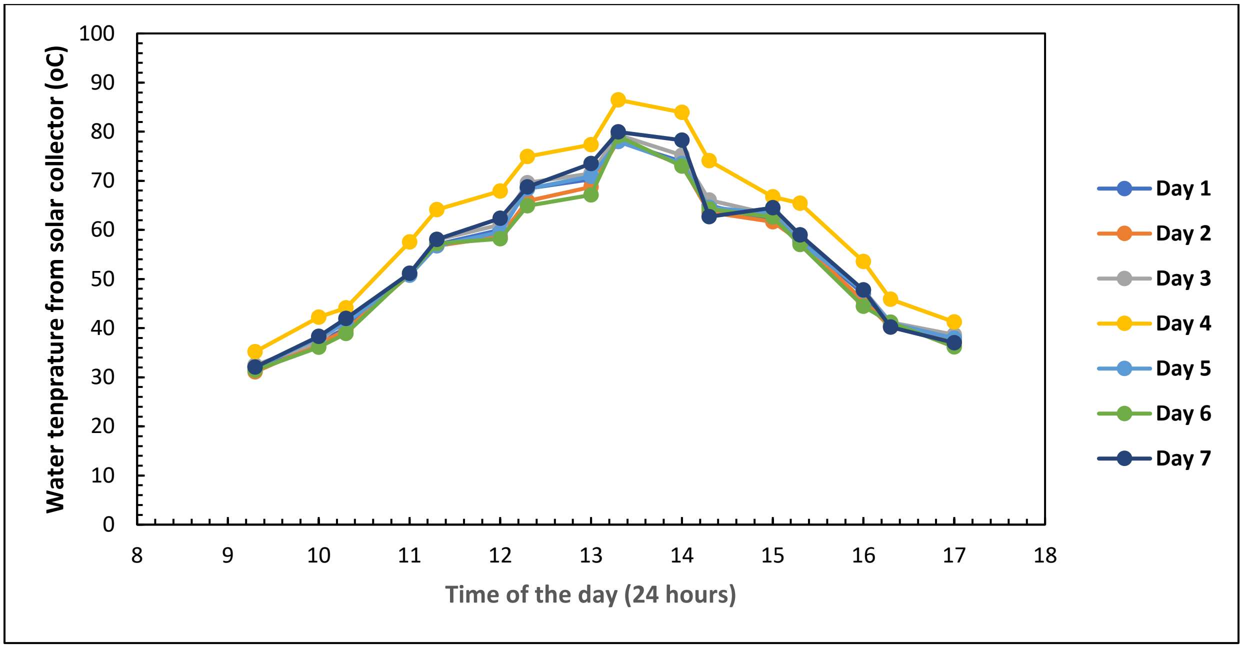


Figure 4: Water temperature into still from solar collector (ºC) for various times of the day for selected days in October, 2020

Table 3: Solar Hourly Global Radiation Values (W/m^2)- for selected days in October, 2020

Time	Day1	Day2	Day3	Day4	Day5	Day6	Day7	
8.0	320.67	317.50	319.00	335.95	313.29	310.09	305.11	
8.5	360.72	354.03	357.42	374.29	352.42	348.82	350.34	
9.0	410.98	402.64	409.28	430.74	401.53	397.42	388.59	
9.5	474.76	465.59	473.76	497.45	463.84	459.09	453.07	
10	533.78	515.84	533.18	557.84	521.50	516.17	521.65	
10.5	576.87	550.37	575.87	607.66	563.60	557.83	561.02	
11	615.87	613.86	616.47	646.29	601.70	595.55	600.36	
11.5	705.86	691.68	703.86	741.05	689.63	682.57	680.04	
12	786.98	769.75	779.14	820.10	768.88	761.01	758.99	
12.5	768.98	753.98	765.24	810.50	751.29	743.60	749.52	
13	750.87	750.11	748.93	780.38	733.60	726.09	730.71	
13.5	730.98	717.48	732.17	764.78	714.17	706.86	705.47	
14	721.98	714.59	721.98	760.08	705.37	698.15	680.60	
14.5	660.97	652.38	655.22	690.98	645.77	639.16	631.91	
15	588.87	586.21	575.92	609.72	575.33	569.44	558.07	
15.5	470.48	464.36	469.54	492.02	459.66	454.95	454.98	
16	387.87	397.83	388.22	406.63	378.95	375.07	370.19	
16.5	320.65	320.48	322.29	340.40	313.28	310.07	312.30	
17	236.87	234.79	235.90	246.70	231.42	229.05	232.59	

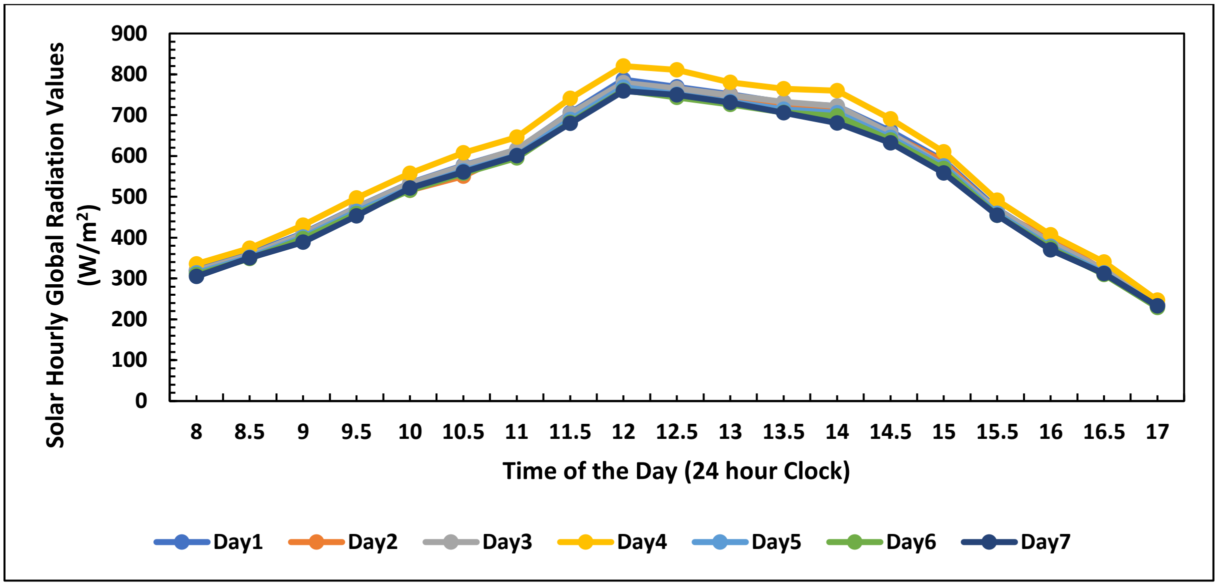


Figure 5: Solar Hourly Global Radiation Values (W/m^2) for various times of the day for selected days in October, 2020

10.0 Analysis of Data generated by the fabricated rig.

Table 1 and Figure 3 show the variation of distillate versus time for the period of seven days. Table 1 also shows the average daily ambient temperatures. Table 2 and Figure 4 show the water temperature into still from solar collector (^{o}C) while Table 3 and Figure 5 show the solar hourly global radiation values (W/m^2) for various times of the day. The Average solar intensity for the various days considered were measured using the solarimeter while the temperatures were generated using type K thermocouples.

For all the seven days considered during the testing of the rig, the ambient temperature averages 31.1 °C throughout the day for the seven days considered. From the daily measurement obtained (Figure 5), it was observed that minimum solar radiation occurs between the hours of 8:00 am and 9:00 am during which the amount of distillate obtained was also the lowest. Moreover, it was observed that even though the solar radiation was highest between the hours of 12:00 noon and 1:00 pm, and the maximum distillate yield was obtained be- tween the hours of 1:00 pm and 2:00 pm for the seven days considered.

11.0 Conclusion

Freshwater scarcity is a big issue in various communities in Nigeria especially isolated communities in rural areas. This fact and the abundance of untreated well water and water from streams and rivers in most region in the country is the main motivation to undertake this evaluation. The results generated by this fabrication justify that Single-effect solar stills are a practical solution to the purification of water in rural areas in the country.

This paper has shown that distillation of water using solar still basin is an economical method to get portable drinking water in rural areas. Salt, heavy metals, bacteria and other impurities and contaminates which are to be removed completely in this distillation process. The solar still fabricated has been proven to be one of best technology for water purification because they do not need electricity which is unavailable in most rural areas in Nigeria.

The implications of the results from the design are for the development of a robust and dynamic single slope solar still system. With this type of design, it is easy to change the inclination angle. This has the potential and capacity to produce distilled water for domestic, industrial and commercial purposes irrespective of the geographical location. The fabricators recommend the mass fabrication of this rig for deployment in rural areas where portable drinking water is unavailable.

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