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Development of A Laboratory-Scale Solar Water Distiller

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ABSTRACT

In this work, a solar water distiller capable of converting impure/saline water into pure/potable water for laboratory and small scale purposes was designed. The design was based on heat transfer processes that involve radiation, convection and conduction. The designed distiller of $0.70m^2$ base area was constructed from mild steel sheet, glass, wood, glass fibre, aluminium sheet and angle iron. Performance evaluation of the constructed distiller was carried out in the month of April, 2014.on the average, The designed model produced 1.7litres of pure water averagely from 21litres of brine water in a period of six hours of a sunny day at an average solar insolation of 547.36W/m2 (15th – 21st of April 2014). The thermal efficiency of the distillation system is 29%. It is recommended that further work be done to improve the efficiency of the system, ascertain the purity of the distilled water produced and provide a flush in the basin for draining the impure water when necessary.

Keywords : Basin, Brine, Distiller, Evaporation, Solar, Temperature, Water.

I. INTRODUCTION

Distilled water is that water that is free from mineral ions, micro-organisms or other forms of impurities. It is safe to drink and can be used for both industrial and research purposes.

About 70% of our planet is covered with water, yet of all that only about 2% is fresh water and of thatabout1.6% is polar ice caps and glacier leaving only 0.4% as drinkable water from underground wells or rivers and streams (Greg, 2012). Despite the amazing amount of technological progress and advancement that the current world we live in has undertaken, a lot of people still do not have access to clean and safe water. In addition, water borne diseases and the absence of sanitary domestic water is one of the leading causes of death worldwide. Clearly, the inadequacy of affordable and readily available potable water is an important and pressing problem facing the world today. To solve or reduce this problem, various water distillation and purification systems have been produced. Generally, water distillation process employs evaporation and condensation to separate pure, fresh water from its contaminants.

The distilling process relies on the principle that most solid minerals found in water have higher boiling or sublimation points than water. Due to the fact that all of the minerals which give water its flavor get removed during the distillation process, distilled water has a noticeable bland taste.

Solar Distillation is a tried and true technology which was first known and used by Arab alchemists as far back as 1551. Naturalists and other scientists who used it over subsequent centuries include Della Porta in 1589,Lavoisier in 1862 and Mauchot in 1869 (Akash *et al*, 1998).

The first conventional solar distillation plant, also known as solar still plant, was built in 1872 by a Swedish Engineer Charles Wilson in the mining community of Las Salinas in what is now northern Chile (Region II). This distillation system was a large basin used for supplying fresh water from brackish feed water to a nitrate mining community. The plant used wooden bays which had blackened bottoms using logwood dye and alum. The total area of the distillation plant was 4,700 square meters and on a typical summer day this plant produced 4.9kg of distilled water per square meter of still surface or more than 23000 litres per day. Solar water distillation system can effectively remove bacteria, E-coli, cholera, botulinus, parasites, salt/minerals such as Na, Ca, As, Fe and Mn, heavy metals and TDS (Kumar *et al*, 1989, Campbell and Norman, 1998).

Distillation systems are categorized based on the source of energy, into those that use electricity as a source of energy and those that use Sun energy which are known as solar distillation system or solar still. Solar distillation systems include wick type solar still, basin type solar still and conical type solar still (Malik *et al*, 1982; Sahoo *et al*, 2007, Tiwari, *et al*, 2003).

Solar water distillation is considered an appropriate technology because it operates on the same principle that produce rain fall (i.e. precipitation), purifying water through a process of evaporation, condensation and collection. This solar still process can be performed by utilizing the available energy of the Sun to evaporate water (Cooper, 1973). Dissolved metal and minerals, such as arsenic, barium, cadmium, chromium and lead are separated from contaminated water. Still also removes salts and biological contaminants such as E-coli (Sahoo *et al*, 2007).

A conventional solar still is a box with glass roof, referred to as a glaze, set at an angle from the horizontal to ensure optimal sun exposure. This angle is roughly equal to the latitude of the location. The distiller faces south if in the northern hemisphere, north in the southern hemisphere (Sahoo *et al*, 2007, Tiwari, 2006).The parts of the solar water distiller or solar still include the still basin, sidewall, top cover, channel, support for the top cover and the collector (Mehta *et al*, 2011).

Commonly available machines or systems for purification of water are very expensive to purchase or maintain by most rural dwellers. To that end, provision of a cheap alternative for rural dwellers becomes imperative and justifies a work aimed at designing and constructing a home size solar water distillation system that is relatively cheap, portable and depends solely on renewable solar energy. The work had, as its objective, the design of a small scale solar water distiller capable of producing two litres of distilled water per day for laboratory and domestic use; to construct an affordable home size solar water distiller using available materials and to evaluate the performance of the home size solar water distiller.

II. DESIGN THEORY, CALCULATIONS AND CONSTRUCTION

In most cases, the distillation system is based on evaporation and condensation which is outlined in the method of operation of various types of distillation systems.

2.1 Principle of Operation

The small size solar water distiller is an airtight basin, constructed out of mild steel with a glass cover of transparent material like glass; plastic etc. The inner surface of the rectangular base is blackened to efficiently absorb the solar radiation, incident at the surface.

The solar radiation, after reflection and absorption by the glass cover is transmitted inside an enclosure of the distiller unit. This transmitted radiation is further partially reflected and absorbed by the water mass. The solar radiation finally reaches the blackened surface where it is mostly absorbed. After absorption of solar radiation at the basin liner, most of the thermal energy is transferred to water mass and a small quantity is lost to the atmosphere. Consequently, the water gets heated, leading to an increased difference between water and glass cover temperature. There are basically three modes of heat transfer, radiation, convection and evaporation from the water surface to the glass cover. The evaporated water gets condensed on the inner surface of the glass cover after releasing the latent heat of evaporation. The condensed water trickle into the trough provided at the lower end of the glass cover under gravity. The collected water in the trough is taken out of the system through the channel into the collector.

2.2 Design Consideration and Design Analysis

In designing the system, critical consideration was given to factors such as efficiency, service life, reliability, weight, size, cost of maintenance, simplicity, safety maintenance and convenience of operation, assembly and dismantling, cost and availability of such materials, thermal energy received by the system, Also the design focused on the indispensable qualities of the system which will enhance its acceptability by rural and urban dwellers. These qualities include Cheapness, Ease in operation and maintenance.

1). Design of Still Basin
Determination of the Internal Dimension of Still Basin

The effective volume of the still basin was obtained based on the required volume of water to be treated per batch. The still basin has the shape of a rectangular cuboid; hence the volume is determined using (1).

$$V_{basin} = V_{water} = l \times b \times h \quad (1)$$

For a still basin that is required to treat 2 litres of water per batch, V_{water}= 2 litres

The bottom surface area of the still basin is equivalent to the surface of water exposed to the sun ray and is obtained by (2) (Bird, 2005) thus:

$$A_{basin} = l \times b \quad (2)$$

Where, l and b are, respectively, the internal length and width of the still basin. For this work, portability of the still basin as well as cost considerations dictated the choice of the length and width to be 1.0m and 0.7m respectively; thus to achieve the required basin volume, the height h of the still basin was chosen to be 0.03m.

2) Design of the Side Wall

The dimensions of the end side walls, for wall thicknesses of 20mm, were obtained using equations (3,4 and 5) (Bird, 2005) thus:

$$L = l + 40\text{mm} \quad (3)$$

$$H_1 = h + 25\text{mm} \quad (4)$$

To obtain the requisite inclination of the still basin, the height H_2 of the back side of the still is calculated using (5):

$$H_2 = H_1 + L\tan\theta \quad (5)$$

The angle of inclination is obtained using (6):

$$\theta = \text{Latitude of lcation of Experiment} + 10 \quad (6)$$

For Yola, the location of this work with Latitude =9.2034°N, the angle θ is obtained as:

$$\theta = 9.2034 + 10 = 19.2034°\text{N}$$

Where, θ is the angle of inclination or slope angle (Sardella, C. S. E., 2012 and J.B Hussein et. al, 2017), $\theta \geq 10°$ Dimension of the back side wall is obtained by (7) and (8) (Bird, 2005) thus:

$$\text{Length} = B \quad (7)$$

$$\text{Width} = H_2 \quad (8)$$

$$B = b + 40\text{mm}$$

Dimension of the front side wall is obtained by (9) and (10) (Bird, 2005) thus:

$$\text{Length} = B \quad (9)$$

$$\text{Width} = H_1 \quad (10)$$

3) Design of the Glass Cover

The passage from where irradiation occurs on the surface of the basin is the Glass cover. Also, it is the surface where condensate collects. It can be circular, rectangular or conical. It can be made of materials such as glass and polythene. The thickness of the glass, t was tentatively chosen based on available standard glass in the market. Thereafter, the dimension of the glass cover was determined geometrically using the obtained dimensions of the outer walls of the still basin.

4) Design of the Channels

The channels is the passage where the condensate formed which slide over the inner surface of the inclined glass cover falls in as pure water.

The volume of the channel is obtained by (11) and(12) (Bird, 2005) thus:

$$V_{innerchannel} = ½\pi r^2 l_{c1} \quad (11)$$

$$V_{outterchannel} = \pi r^2 l_{c2} \quad (12)$$

Where l_{c1}= B; r = 15mm; l_{c1} = B=740mm and l_{c2} =915mm

5) Design of the Collector

The collector is a container where the distilled water is kept. The dimension of the collector is determined based on the required volume capacity of the collector.

The volume of the collector, according to Bird (2005), is obtained by (13):

$$V_{collector} = \frac{1}{3}\pi h(R^2 + Rr + r^2) \quad (13)$$

where, $h -$ The height of the collector; $R -$ Top collector radius, $r -$ Bottom collector. Radius, r =177mm.

6) Frame Design

The frame provides support for the glass cover and the entire system. A fillet form of welding is chosen for the design of frame and weld. Thus the effective weld force or strength of fillet P is given by (14) (Khurmi and Gupta, 2002) as:

$$P = L \times t \times \delta \quad (14)$$

Where; $\delta -$ The permissible stress for axial compression or tension and is usually given as 140MPa (Khurmi and Gupta, 2002); $L -$ The total length of weld or welded length; $t -$ The effective throat thickness and it is usually

$$t = Kx \quad (15)$$

Where; $x -$ is the size of weld, $K -$ A constant

7) Design Results

The major design parameters are summarised in Table 1.

Table 1: Design Parameters

Parameter	Value
Area of collecting surface (glass)	$0.815m^2$
Area of basin	$0.7m^2$
Slope angle of cover	19.2034°
Thickness of glass	0.003m
Length of glass	1.101m
Width of glass	0.740m
Height of backside	0.417m
Height of front wall	0.055m
Length of still	1.040m
Width of still	0.740m

✓ Thermal Efficiency of the System

The thermal efficiency of the system is obtained from (16) (Hamdan, et al., 1999) thus:

$$\eta = \frac{mL_w}{GA_g\Delta t} \quad (16)$$

Where; $m -$ Mass of distilled water in a time interval, $A_g -$ Surface area of the collecting glass, $G -$ Heat radiated on the system, $\Delta t -$ Time interval taken to radiate, $L\dot{m}_w -$ The latent heat of evaporation in joule/kg.

$L_w = 3.1615 \times 10^6(1 - 7.6160 \times 10^{-4}T)$ for temperatures higher than 70°C and

$L_w = 2.4935 \times 10^6(1 - 9.4779 \times 10^{-4}T + 1.3132 \times 10^{-7}T^2 - 4.7974 \times 10^{-9}T^3)$ for temperatures less than 70°C.

✓ Distiller Construction

Construction of the distiller involved the fabrication of the various parts that make up the still and then assembling the fabricated parts to form a single product.

1). Manufacturing Details

Still basin was made from mild steel sheet. The mild steel sheet was measured with a measuring tape and marked out with a scriber according to the dimensional requirement ($1000mm \times 700mm \times 30mm$) of the still basin, then cut using a hack saw and welded into shape of the still basin.

Side walls were fabricated from plywood measuring and marking out according to the required dimensions of $1040mm \times 740mm$; $417mm \times 700mm$; $55mm \times 700$ mm; and $(1040$ mm $\times 417$ mm$) \times 2$; the two 1040 mm $\times$ 417 mm pieces were marked to obtain a $19.2034°$ inclination. The pieces were then joined by nailing.

Top cover was cut from a glass sheet of 3mm thickness. The glass was measured, marked and cut into the required dimension ($1101mm \times 740mm$) with the aid of diamond glass cutter.

Frame was made from angle iron. The angle iron was measured with a measuring tape and marked out with a scriber according to the dimensional requirements ($1040mm \times 740mm \times 805mm$) of the frame, then cut and welded into shape of the frame.

Channel was constructed from PVC pipes. The PVC pipes was measured with a measuring tape, marked with a scriber and then cut into the required dimension. The collector was standard and bought from the local market.

2). Assembling and Finishing

After the successful fabrication and purchasing of parts that make up the still system, what followed was assembling which was done based on Appendix I. Firstly, the still basin was inserted into the side wall which had already been insulated, then the channel was fixed on the side wall and the top cover which is the glass was used to cover the system. The system was then inserted into the frame and the channel connected into the collector.

At the finishing stage, the weldment and rough edges and surfaces were dressed to give a smooth surface using hand file, electric file and sand paper. Then the frame was painted to prevent rusting and to give it attractive look.

The total cost of production of the distiller was ₦23, 225.00 as of December 2015 market prices.

III. RESULTS AND DISCUSSIONS

Testing was carried out between 15th and 21st of April, 2014 and the results are presented as follows:

A. Unloaded Testing

The result of performance analysis presented in fig. 1 shows the effect of solar radiation on the unloaded distillation system with time. This figure comprises of temperature of the basin, glass and ambient with respect to time in hours.

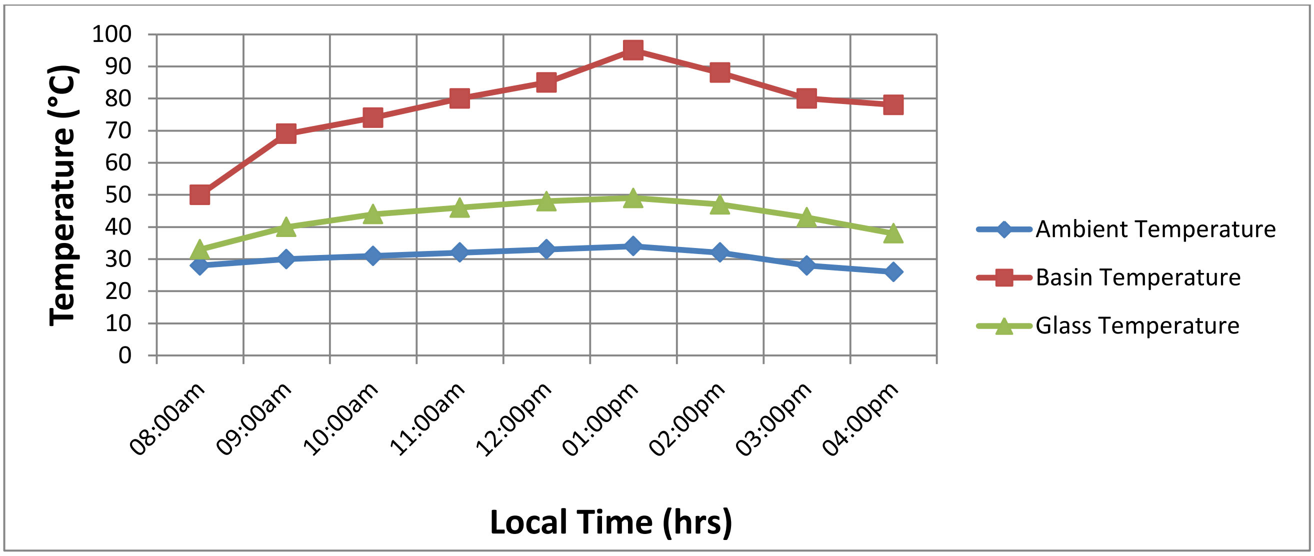

Figure 1: Unloaded Test Still Temperature against Local Time at an Average Solar Radiation of 547.36W/m^2.

The figure shows the effect of solar intensity on the basin temperature. The temperature of the basin increased from a temperature of 50^{o}C at about 8:00am up until about 1:00pm when it reaches a maximum temperature of about 95^{o}C after which it then decreased. This is in accordance with expectations since the intensity of solar radiation starts decreasing after reaching a peak.

B. Testing under loaded condition

The result of performance analysis presented in Figures 2 and 3 shows the effect of solar radiation on the loaded distillation system with time. The figure shows the temperature of the brine used for the performance test; that of the covering glass and the ambient temperature as well as the quantity of distilled water produced with respect to time in hours.

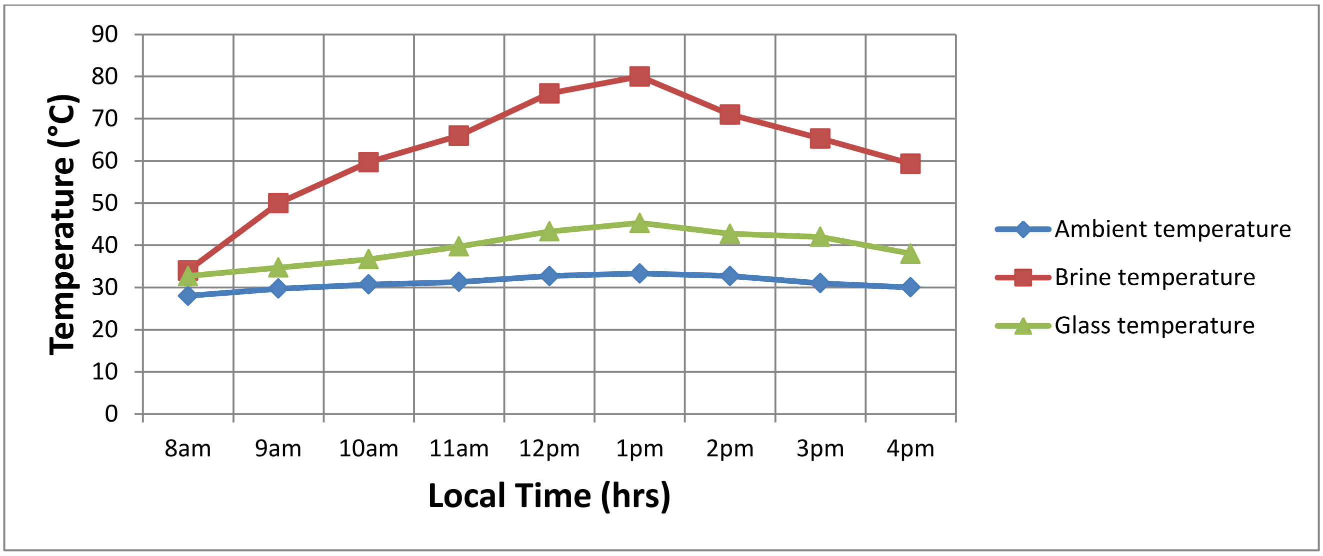

Figure 2 : Load Test Still Temperature against Local Time at an Average Solar Radiation of 520.29W/m^2 and Relative Humidity of 49.57%

Fig. 2 shows the effect of solar intensity on the brine temperature for the distillation system with respect to time. The brine temperature of 34^{o}C began to increase from about 8:00am till about 1:00pm when it reached a maximum temperature of80^{o}C and began to decrease. It also shows the effect of solar radiation on the temperature of the top cover (glass) of the distillation system. The temperature of the glass was 32.7^{o}C at about 8:00am and increases lightly to a temperature of 34.7^{o}Cat about 9:00am,these continue till about 1:00pm when it attained its maximum temperature of 45.3^{o}C and then decreased as the intensity of the sun decreases.

The figure also shows the effect of solar radiation on ambient temperature. The ambient temperature was 28^{o}C as at 8:00am but increased to maximum temperature of 33.3^{o}C at 1:00pm, then decreased to a temperature of 30^{o}C by 4:00pm.These trends are similar to those of Mehta et al (2011) and Tenthani et al (2012). It is deduced that there is direct proportionality between the intensity of the sun and the temperature of the system with respect to time.

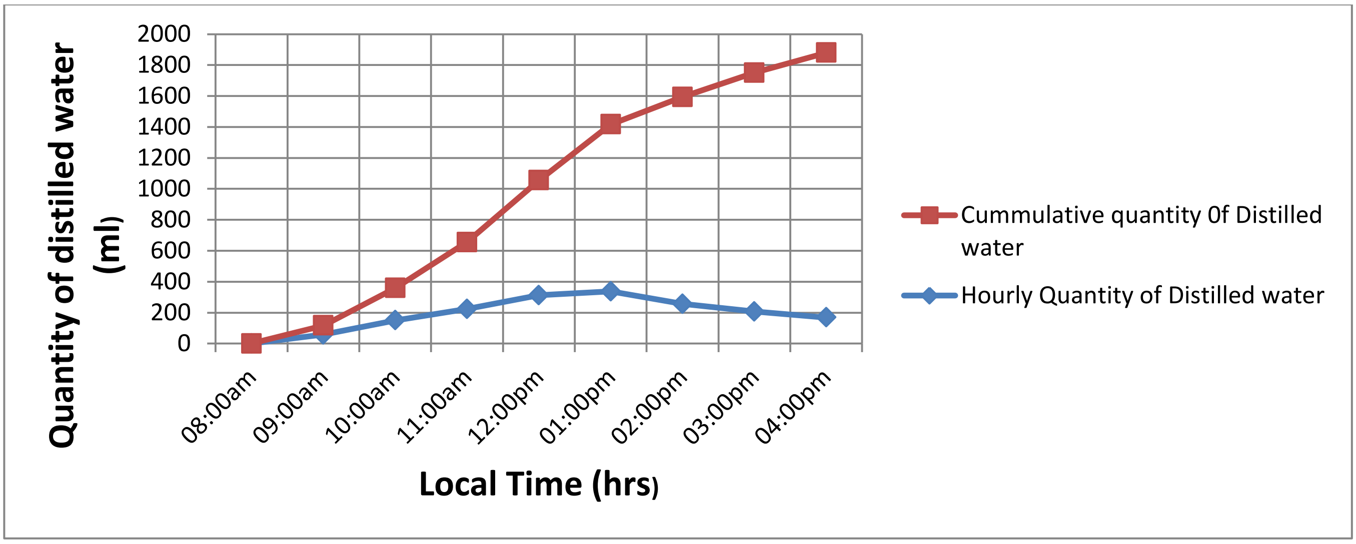

Figure 3: Quantity of Distilled Water Produced versus Local Time at an Average Solar Radiation of 520.66W/m^2 and Relative Humidity of 49.57%

Fig. 3 shows the quantity of distilled water produced per hour and the cumulative quantity produced per day. From this result, it is observed that there is a corresponding increase in the quantity of distilled water produced as the temperature increases with time. It is also observed that more distilled water was produced during the period of 11:00am – 2:00pm with the highest quantity of distilled water of 336.7ml produced at about 1:00pm when the solar intensity was at its zenith and temperature was 80°C while at about 4:00pm a cumulative quantity of 1,711.7ml (that is 2.20L/m^2 of solar collector surface) was produced. This trend is similar to that of Silva et al (2014). However, the quantity of distillate obtained is lower than that obtained by Silva et al (2014) and Thentani et al (2012) but is within the range obtained by Cappelletti (2002). From the results it was deduced that the highest quantity of pure water is produced when the intensity of the sun is at its zenith. The efficiency of the system was calculated as 29%.

IV. CONCLUSION

In conclusion, the designed and constructed solar distillation system provides daily consumption of 2 litres of water per day and gives the overall thermal efficiency of 80%. A high basin/brine temperature is often associated with high productivity, and the reverse is true for the glass cover. A high solar intensity corresponds to high productivity.

The solar distillation system is relatively inexpensive low-technology system, especially useful in the countries where the need for small plant is promising.
The home size solar distillation system may be considered as one of the alternative for fresh water production in developing countries where potable water is scarce in quantity and quality needed for drinking, sanitation and other domestic purposes. The work recommend that in the regions and periods were solar radiation is low, sun tracking devices can be employed to improve the performance of the distillation system or thermal storage medium may also be used, the quality of distilled water produced should be analyzed to ascertain its purity and provision of opening should be made for occasional flushing of the solar distillation system basin.

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VII. APPENDIX

Working Drawing of the Small Scale Laboratory Solar Water Distiller