International Journal of Scientific & Engineering Research, Volume 5, Issue 1, January-2014
ISSN 2229-5518

# Design and Fabrication of a Single Slope Solar Still with Variable Collector Angle

**J. D. Obayemi, F. O. Anafi, S. T. Azeko, E. K. Arthur and D. Yiporo**

**Abstract -**This work presents the development of a flexible, efficient, robust and low cost single solar still. Experimental investigations were carried out on two single slope solar stills: a modified solar still with variable collector/inclination angle (still A), and a conventional solar still with rigid angle of collector/inclination (still B). The significance of the design is its ability to be able to optimally function properly by variation of the angle at which solar radiation is optimally incident on the system at different locations and time. Also, the experiment was carried out at latitude of 11º 20′ in Samaru, Zaria – Nigeria, during an average period of solar radiation. Experimental results between the hours of 8.00 am and 5.00 pm for a period of 5 days were carefully obtained and analyzed. The results clearly show that distillate peak yield occurred between 2.00 pm and 3.00 pm while minimum yield was obtained between 8.00 am and 9.00 am during the period of experiment. It was observed that, still B had an average yield of 1.366 liter/day/m$^2$ as compared to still A, (1.407 liter/day/m$^2$). Furthermore, the results obtained for the two single slope solar stills were analyzed using a statistical model (a paired T-test). The outcomes clearly suggest that, there is no significant difference between the distillate of still A (efficiency of 42%) and still B (efficiency of 39%). Implications of the results from the design are discussed for the development of robust and dynamic single slope solar still systems with variable collector/inclination angle. This has the potential and capacity to produce distilled water for domestic, industrial and commercial purposes irrespective of the geographical location.

**Keywords:** Single slope solar still, variable collector angle, distillate, Paired T-test.

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## 1 INTRODUCTION

It is an established fact that, water is the most abundant resources on earth. Water is essential for human use, covering approximately three-quarters of the planet's surface [1]. About 97% of the earth's water is salt water in the oceans, while 3% of all fresh water is in the ground water, lakes and rivers. These together, supply most of the water needed by humans and animals [1], [2]. Despite the abundance of water, availability of portable water is one of the major challenges in developing countries [2]. Water shortage is a worldwide problem, and of which 40% of the world population is suffering from water scarcity [1], [2].

On a global scale, man-made pollution of natural sources of water contributes largely to the shortage of fresh-water [3]. One of the inexhaustible sources of water is the ocean, but their main setback is the high salinity [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16]. Desalination could be an effective approach that can be used to establish a solution based approach for problems associated with water-shortage. This may be mixed with brackish water to increase the amount of fresh-water and reduce the concentration of salts [15], [16].

The availability of cost effective approach to harness the solar energy in solving the problem associated with potable water can not be overemphasized. This is a major challenge in the developing countries today. Many health disorders in rural communities in the developing countries have been traced to intake of contaminated water [1], [2]. Apart from drinking, pure water is needed to meet the requirements of medical, pharmaceutical and industrial applications [16]. However, it is imperative to know that, energy plays a vital role in the provision of portable water for both household and industrial use. Solar based energy can be used effectively for solar heating, solar cooking, generation of electricity and doing some mechanical work. [17].

Solar still, also known as solar distiller is a simple device that uses heat directly from the sun. This heat can be used to drive evaporation from humid soil, and ambient air to cool a condenser film in a simple manner to purify brackish/saline water into potable water. A solar still operates on the same principle as rainwater; where evaporation and condensation process take place. The water from the oceans evaporates, only to cool, condense, and return to earth as rain. When the water evaporates, it removes only pure water and leaves all contaminants behind. Solar still has been proven to be the best solution to solve water problem in remote arid areas and developing countries [3], [4], [18], [19], [20], [21], [22]. Purifying water through distillation is a simple, yet effective means of providing portable water in a reliable and cost-effective manner. Solar stills effectively eliminate all water borne pathogens, salts, and heavy metals, and produce ultra-pure water to be superior to most commercial bottled water sources [18], [19], [20], [21], [22]. Many researchers [3], [4], [7], [8], [13], [14] have

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found the productivity for different brine depths in the basin of a single-slope single basin solar still.

**Nomenclature**

$\alpha_w$ - Absorptivity of the water mass
$\alpha_P$ - Absorptivity of the absorber plate (Aluminium)
$\alpha_s$- Absorptivity of the still
$\alpha_g$ - Absorptivity of the glass cover
$\tau_g$ - Transmissitivity of the glass cover
$\tau_a$ - Transmissitivity of the aluminium foil
$\rho_a$ - Reflectivity of the aluminium foil
$\varepsilon_g$ - Emissivity of the glass cover
$\varepsilon_P$ - Emissivity of the aluminium plate
$G_s$ - Average solar intensity/radiation, W/ $m^2$
$C_{wb}$ - Thermal capacity of the still, water and basin, J/C$m^2$
$C_g$ - Thermal capacity of the still, water and basin, J/C$m^2$
$C_{gs}$ - Thermal capacity of the stilland ground, J/C$m^2$
$q_e$ – Heat flux by evaporation and condensation, W/ $m^2$
$q_r$ – Rate of heat transfer from the water surface to the cover by radiation, W/ $m^2$
$q_b$ - Heat loss through base and perimeter of base (W/ $m^2$)
$q_c$ - Heat flux from the water surface to the cover by free convection (convective loss) transparent cover to ambient air, W/ $m^2$
$q_{ga}$ - Rate of heat flux transferred from glass cover to ambient, W/ $m^2$
$h_c$ – Heat flow through convection on the water and surrounding,W/$m^2$.K
$v$ = Wind velocity, mt/s
$h_b$ - Heat flow from absorber to basin and surroundings, W/$m^2$.K
$h_{fg}$ - Convective heat transfer coefficient between cover and ambient, W/$m^2$.K
$T_w$ - Average water temperature in the basin, °C
$T_g$ – Average temperature of the glass cover, °C
$A_c$ - Effective area of the collector, $m^2$
$F_s$ - Shape factor which is taken as 0.9
$A_g$ – Effective area of the glass, $m^2$
$A_w$ – Effective area of water film, $m^2$
L – Latent heat of vaporization and condensation
$W_{wb}$ - Specific humidity of air going towards the water basin from transparent cover
$W_g$ - Specific humidity of air going towards the transparent cover from the basin
m - Mass flow rate, kg/s
$\sigma$ - Stefen- Boltzman constant, = $56.7 \times 10^{-9}$ W/ $m^2K^4$
$P_w$ – Saturation pressure of water at $T_w$, MN/$m^2$
$P_g$ – saturation pressure of water at Tg, MN/$m^2$
Rg – thermal resistance of the glass, $m^2$K/W
$R_w$ – thermal resistance of the brackish water, $m^2$K/W
$R_{ab}$ – thermal resistance of the absorber, $m^2$K/W
$R_{ra}$, $R_{ca}$ – thermal resistance between the glass surface and the ambient due to radiation and convection respectively, $m^2$K/W
$R_{ins}$, $R_{rca}$ – thermal resistance between the insulator and the ambient air due to radiation and convection respectively, $m^2$K/W
$R_r$, $R_c$ – thermal resistance of the moist air in the enclosure due to radiation and convection respectively, $m^2$K/W.
$I_{st}$ – Solar radiation on the glass cover of the solar still, W/ $m^2$
$I_w$ – Solar radiation on the water, W/ $m^2$

Over the last few years, there have been efforts to develop simple solar distillation technologies that could be applied in different locations to meet the need of drinking water [3], [4], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [18], [19], [20], [21], [22]. Studies over the years have shown that most stills built were based on the same principles [23]. Despite this fact, there have been many variations in their geometry, materials, methods of construction, and operation have been incorporated. The cost of building and operating a conventional still is relatively low compared to those involving sophisticated designs. However, the conventional single basin type solar stills [4], [7], [14], [17], [21], [22], [23] are proven to have a low thermal efficiency with low daily distillate productivity [24]. The efficiency and yield of the conventional solar still depend on different factors: the design and functionality of the still, location, and weather conditions [25]. Their low thermal efficiency is due to the considerable shadow caused by the walls of the basin that tend to decrease the absorption of solar radiation that could have been used for water distillation process.

In order to improve the performance of a conventional solar still, several other designs have been developed, such as the double-basin type [26], multi-basin [27], [28], inverted trickle [29], multi-effect [30] and regenerative [31] with reflectors [32]. The methods that have been attempted to increase productivity ranges from decrease the volumetric heat capacity of the basin, attachment of additional sub-systems and other major departures from the simple configuration [33], [34], [35], [36], [37], [38]. The enhancement of the productivity of the solar desalination system in a certain location could be attained by a proper modification in the system design. However, the increase in the system productivity with high system cost may increase also the average annual cost of the distillate [39], [40].

This current work explores the design and efficiency evaluation of a flexible, robust and low cost solar still with variable collector angle. This is capable and has the potential of producing distilled water for domestic, industrial and commercial purposes when scale-up, irrespective of the geographical location. Furthermore, in this work, Zaria (11° 20′, a region in Northern Nigeria) was used as a case study to evaluate the performance of the modified solar still. The implications of the results from the design are discussed for the potential development of a robust and dynamic single slope solar still system with variable collector/inclination angle. This has the potential and capacity when scale-up to produce distilled water for both domestic and commercial purposes irrespective of the geographical location. Statistical analysis was also used to compare the performance of the fabricated variable/inclination collector single slope solar still (still A) with the positive control (still B).

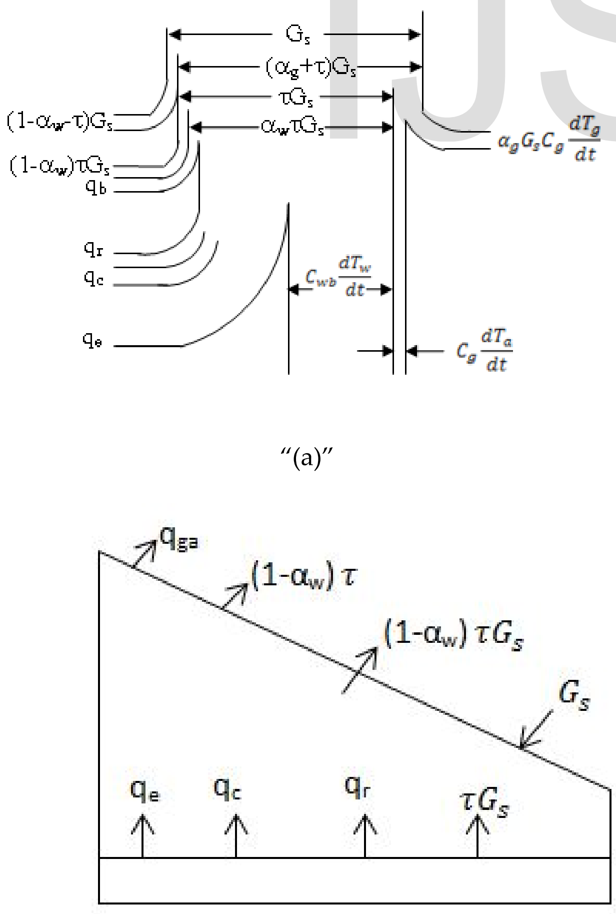
## 2 THEORETICAL ANALYSIS OF SOLAR STILL

### 2.1 Thermal Analysis

Assumptions that were considered in this present theoretical analysis include [41]:

1. Equal area of glass cover ($A_g$) to water film ($A_w$).
2. Both the water film and the glass cover are gray surfaces.
3. Constant temperatures ($T_w$) and ($T_g$) were maintained for the water film and glass cover respectively.
4. There is constant and equal specific heat capacity for feed, brine, and distillate.
5. The sky was considered as a black body.
6. Exposure of glass covers only to the sky

Figure 1 shows the heat transfer equation on the still according to Sankey, 1889, the basis for heat transfer equation for a single slope solar still



“(a)”

“(b)”

Fig.1: Heat Flux Relations in a Solar Still (Sankey Diagram)

Heat balance on the absorber (basin water) is given by:

$$\alpha_w \tau_g G_s = q_c + C_{wb}\frac{dT_w}{dt} + q_e + q_r + q_b \tag{2.1}$$

Similarly, the heat balance on the glass cover and water basin is shown as:

$$q_e + q_c + q_r + \alpha_g G_s = q_{ga} + C_{gs}\frac{dT_g}{dt} \tag{2.2}$$

Hence, the overall heat balance equation on the solar still is obtained by combining equations (2.1) and (2.2) giving as. $(dT_w)/dt = 0$

Thus:

$$\alpha_g G_g + \alpha_w \tau G_g = q_{ga} + q_{rb} + C_{ga}\frac{dT_g}{dt} + C_{wb}\frac{dT_w}{dt} \tag{2.3}$$

At steady state, (i.e. when the temperature of the water does change with time), then Equation (2.3) becomes:

$$q_e = \alpha_w \tau_g G_s - (q_b + q_r + q_c) \tag{2.4}$$

Where, $q_r = F_s A_c \sigma(T_w^4 - T_g^4)$ (2.5)

$$q_c = h_c(T_w - T_g) \tag{2.6}$$
$$q_b = h_b(T_w - T_a) \tag{2.7}$$
$$q_e = mL(W_{wb} - W_g) \tag{2.8}$$

More explicitly, the heat transfer in the solar still between the glass cover and the water surface is by convection which is accompanied by evaporative mass transfer (water vapor) and radiation. Hence the heat transfer per unit area per unit time between the water surface and glass cover due to convections, radiation and evaporation are given respectively as [42]:

$$q_c = 7.734x10^{-4}\left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{2.65P_T - P_w}\right]^{1/4}(T_w - T_g) \tag{2.9}$$

$$q_r = \frac{A\sigma(T_w+273)^4 - (T_g+273)^4}{1/E_c + A_c/A_g\left[1/E_g - 1\right]} \tag{2.10}$$

$$q_e = 16.273 \text{ x } 10^{-3}\frac{q_c(P_w - P_g)}{T_w - T_g}h_{fg}q_c. \tag{2.11}$$

### 2.2 Thermal circuit of the solar still

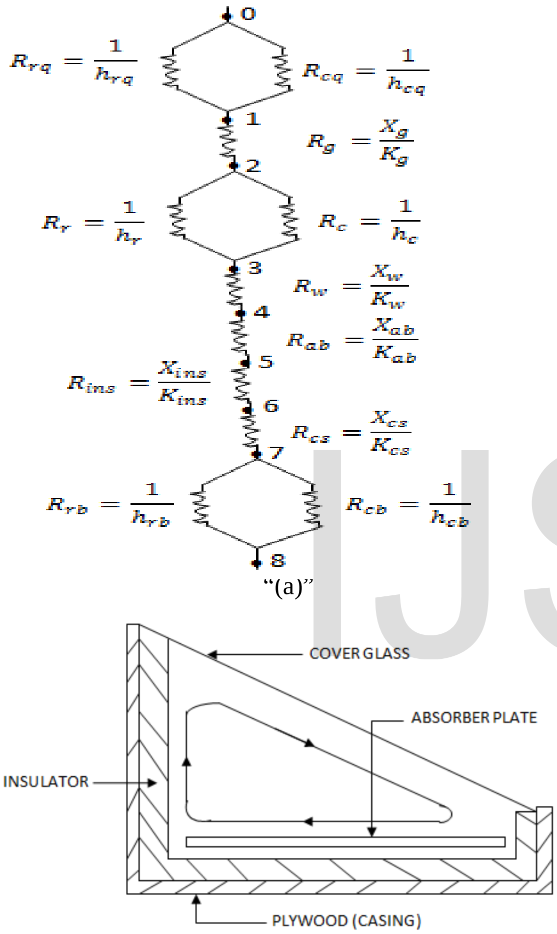
Figure 2 describes the thermal circuit of the solar still. However, from the thermal circuit configuration of the solar still,

$$R_{5,6} = R_{ins}, R_{4,6} = R_{ab}, R_{6,7} = R_{cs}, \tag{2.12}$$

$$R_{4,8} = R_{5,6} + R_{6,7} + R_{7,8} + R_{4,5} \quad (2.13)$$

$$R_{4,8} = \frac{X_{ins}}{K_{ins}} + \frac{X_{cs}}{K_{cs}} + \frac{X_{ab}}{K_{ab}} + \frac{1}{h_{cb}+h_{rb}}. \quad (2.14)$$

But, $h_{rb}$ is very small component with $h_{cb}$, hence neglected



"(a)"

"(b)"

Fig. 2: Thermal Circuit of the Solar Still.

$X_{ab}/K_{ab}$ is very small since $K_{ab}$ is very large compared to $X_{ab}$

Hence, $X_{ab}/K_{ab}$ term is neglected

$$R_{4,8} = \frac{X_{ins}}{K_{ins}} + \frac{X_{cs}}{K_{cs}} + \frac{1}{h_{cb}} \quad (2.15)$$

But, $q_b = U_b(T_w - T_a)$ Where, $U_b = \frac{1}{R_{4,8}}$

Then $q_b = \frac{T_w - T_a}{R_{4,8}} = \frac{T_w - T_a}{\frac{X_{ins}}{K_{ins}} + \frac{X_{cs}}{K_{cs}} + \frac{1}{h_{cb}}}$ (2.16)

Note that;

$$1/R_{7,8} = 1/R_{cb}, \qquad R_{7,8} = \frac{R_{rb}R_{cb}}{R_{rb} + R_{cb}} \quad (2.17)$$

### 2.3 Overall Efficiency of the Solar Still

For an ideal solar still, the overall efficiency is the ratio of the heat utilized in vaporizing water to the total solar radiation received by the transparent cover (glass):

$$\eta_e = Q_e/G_s \text{ x } 100 \quad (2.18)$$

Where, $Q_e$ is called useful energy, which is the heat, used in vaporizing water per unit area per unit time of the absorber. $G_s$ is the average solar radiation.

For the fabricated solar still, the actual efficiency is given as:

$$\eta_e = M_e(I_{st} - I_w)/G_s \text{ x } 100 \quad (2.19)$$

From equation (2.3)

$$Q_e = \alpha_w T_g G_s - (q_c + q_b + q_r) \quad (2.20)$$

Again, the external convection coefficient is a function of wind velocity given as:

$h_{cb} = 5.7 + 3.8v$ [42], [43] (2.21)

Furthermore, the daily distilled water output or solar still production ($M_e$ in kg/m$^2$ day) is the amount of energy utilized in vaporizing water in the still ($Q_e$ in J/m$^2$ day) over the latent heat of vaporization of water (L in J/kg)

$$M_e = Q_e/L = G_s\eta/(I_{st} - I_w) \quad (2.22)$$

$$q_{ga} = \alpha_g G_s + q_c + q_e + q_r \quad (2.23)$$

## 3 MATERIALS SELECTION AND DESIGN

### 3.1 Materials Selection

In this work, primary considerations were focused on ultimate cost of delivered energy in the design and fabrication of the solar stills. These consist of design cost, choices of the materials and cost of labor. Section 3.0 presents two tables (Table 1 and 2). Table 1 summarizes the different materials component of the solar distiller and the basis they were selected, while Table 2 describes the physical dimensions of the solar stills.

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

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

### 3.2 Design Considerations and Calculations

Basic physical dimensions of the solar stills were described in Table 2, while the heat calculation from the design is highlighted in Table 3. This section describes briefly various parameters considered alongside the results obtained in fabrication of the solar still.

Table 2: Physical Dimensions of the solar stills

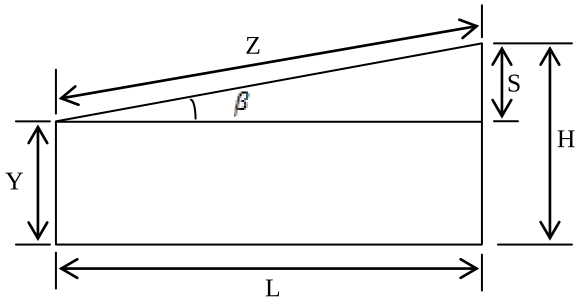
| S/N | Initial Data | Calculation and sketches | Results |
|---|---|---|---|
| 1 | Using<br>$\beta = 11°20'$<br>$L = 860\ mm$<br>$Y = 200\ mm$ |  <br>From simple trigonometry,<br>H = Y + S<br>$H = Y + L\ x\ tan\beta$<br>$H = 200 + 860\ x\ \tan(11°20')$ | H = 372 mm |
| 2 | Transparent cover | $cos\beta = L/Z$<br>$Z = L/cos\beta = 860/\cos(11°\ 20')$ | Z = 877 mm |
| 3 | Effective area of the collector A<sub></sub>c and glass, $A_g$ L = 66 mm, B = 76 mm | $A_c = LxB = 0.66\ m\ x\ 0.76\ m$<br>$A_g = 0.66\ m\ x\ 0.76\ m$ | $A_c = 0.502\ m^2$<br>$A_g = 0.502\ m^2$ |

Table 3: Heat Balance and Energy Vector on the Solar Still

| S/N | Initial Data | Calculation | Results |
|---|---|---|---|
| 1 | $T_w = 49°C =$ 322K<br>$T_g = 41°C =$ 314K<br>$\sigma = 56.7 \times 10^{-9} W/m^2K,\ \varepsilon_g = 0.94$<br>$\varepsilon_c = 0.94 \quad A_c = 0.502m^2$<br>$A_g = 0.502m^2$ | From equation (2.10)<br>The shape or view factor<br>$F_s = \frac{1}{1/\varepsilon_s + \left(A_c/A_g\right)\left(\frac{1}{\varepsilon_g} - 1\right)} = \frac{1}{1/0.95 + \left(0.502/0.502\right)\left(\frac{1}{0.94} - 1\right)}$ | $F_s = 0.806$ |
| 2 | $T_w = 49°C =$ 322K, $T_g = 41°C =$ 314K<br>$F_s = 0.806,\ A_c = 0.502m^2$ | From (2.5), $q_r = F_s\sigma A_c(T_w{}^4 - T_g{}^4)$<br>$q_r = 0.896 \times 56.7 \times 10^{-9} 0.502 \times (322^4 - 314^4)$ | $q_r = 26.248W/m^2$ |
| 3 | V=5$ms^{-1}$ (From IAR) | From equation (2.20) $h_{cb}$=5.7+3.8V= 5.7+3.8× 5 | $h_{cb}$ = 24.7 $W/m^2$ |
| 4 | $X_{ins}$ = 30mm<br>$K_{ins} = 0.038W/m^2K$<br>$X_{cs}$=10mm<br>$K_{cs} = 0.21W/m^2K$ | From equation (2.15)<br>$U_b = \frac{1}{\frac{X_{ms}}{K_{ms}} + \frac{X_{cs}}{K_{cs}} + \frac{1}{h_{cb}}} = \frac{1}{\frac{0.03}{0.038} + \frac{0.01}{0.21} + \frac{1}{24.7}}$ | $U_b = 1.139W/m^2K$ |
| 5 | $T_w = 49°C = 322K$<br>$T_g = 32°C = 305K$ | From equation (2.15)<br>$q_b = U_b\left(T_w{}^4 - T_g{}^4\right) = 1.39(322^4 - 305^4)$ | $q_b = 19.363\ W/m^2K$ |
| 6 | $T_w =$ 322K<br>$T_g = 314K$<br>$P_w = 12.185 \times 10^3 N/m^2$<br>$P_g$=7.78× $10^3N/m^2$<br>$P_T = 101.325kN/m^2$ | From equation (2.9)<br>$q_c = 7.734 \times 10^{-4}((T_w - T_g)) + (\frac{(P_w - P_g}{2.65(P_T - P_w)})\ T_w)^{1/4}(T_w - T_g))$<br>$q_c = 7.734 \times 10^{-4}((322 - 314)) + (\frac{12.185 - 7.78}{2.65(101.325 - 12.185)})\ 322)^{1/4}(322 - 314))$ | $q_c = 0.01186KW/m^2$<br>$q_c = 11.867W/m^2$ |
| 7 | $T_w =$ 322K, $T_g = 314K$<br>$P_w = 12.185 \times 10^3 N/m^2$<br>$P_g$=7.78× $10^3N/m^2$<br>$h_{fg} = 2.3462KJ/m^2$,<br>$q_c$ =11.867W$/m^2$ | From equation 2.11<br>$q_e$=16.226× $10^{-3}\left(\frac{((P_w - P_g)}{(T_w - T_g)}\right) h_{fg}\, q_c$<br>$q_e$=16.226× $10^{-3}\left(\frac{(12.185 - 7.78)}{(322 - 314)}\right) 2.3462 \times 11.867$ | $q_e = 248.75W/m^2$ |

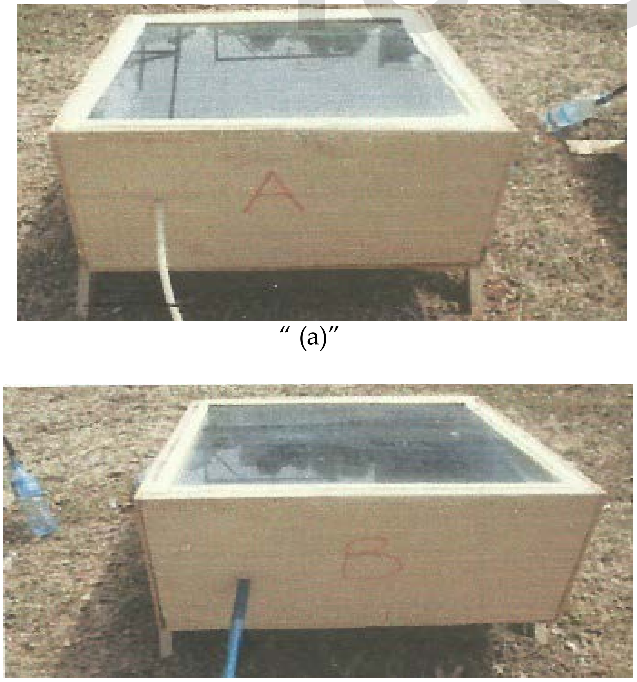
## 4 EXPERIMENTAL PROCEDURES

Section 4.0 describes fabrication of the solar still and experimental steps employed to obtain distilled water.

### 4.1 Solar Still Fabrication

The still boxes were constructed with stiff plywood and four-minute araldite was used to seal up the spaces. Then, the plywood boards were nailed together to reduce heat loss in the system. Aluminum sheets were also used for the absorber/basin due to its high thermal conductivity (229 W/m$^2$). The basin was painted black in order to enhance adsorption of heat by water. The bottom surface of the still basin was also painted black to absorb a large amount of solar radiation.

Moreover, the basin was properly fitted into the plywood boxes before being covered with a 4 mm thick transparent collector glazing. This was inclined together with the condensing glass cover at an angle of 11° as shown in Figure 1. A cylindrical collection trough with diameter was constructed with 1 mm thick stainless steel sheets. It was therefore fitted at the end of the glass slope. The aim was to collect and channel the distillate through a flexible hose into a plastic storage container outside the still. Detailed design analysis of the stills is not presented in this paper, although some designs were captured and parameters were selected based on availability of materials and convenience.



“ (a)”

“(b)”

Fig. 2: (a) Fabricated Single Slope Solar Still with Variable Collector (Still A) (b) Conventional Single Slope Solar (Still B)

### 4.2 Experimental Set up for Distillation

Distillation experiment was carried out using two solar stills, namely: still A and still B. The solar stills were constructed and their efficiencies evaluated at the department of Mechanical Engineering, Ahmadu Bello University (ABU) Zaria. Zaria is in the northern part of Nigeria with latitude $11^0$ 20′ of which the roof angles of both stills were stationed to carry out the experiment. The yields of the solar stills were collected using calliberated measuring jars.

Futhermore, the solar stills were oriented in the north–south direction to receive solar radiation throughout the working hours of the day. Experiments were conducted from 8 a.m. to 5 p.m. in the month of December. Solar radiation, relative humidity, ambient temperature, distillate output, basin, water, and cover glass temperatures were all measured for an interval of 30 min. Lastly, the intensity of solar radiation was measured using a solar radiation recorder (Campbell-stoke, Raj instruments, Ahmedabad, Gujarat, India), and a digital thermometer was used to measure ambient temperature. Calibrated iron-constantan thermocouples were used to measure the basin, water, and glass cover temperatures.

## 5 RESULTS AND DISCUSSION

### 5.1 Performance and Efficiency Evaluation.

Average solar intensity from the Gunn Belani reading obtained for nine (9) sunshine hours is 764 W/m$^2$. These data were gotten from the Metrological unit of the Nigeria College of Aviation Technology (NCAT).

From equation 2.18, the efficiency of the modified solar still for the values of $T_a$=26 °C, $T_c = I_w$ =108 kJ/kg, $I_{st}$ = 3592 kJ/kg and 1.407 liter/m$^2$/shunshine hour was calculated as 42 %. For solar still B, the efficieny was calculated as 39 % using the same parameters with distillate of 1.366 liter/day/m$^2$.

It is clear that, for all the five days of experiments, the ambient temperature is higher than 25 °C from the morning hours. Also, the maximum ambient temperature recorded was 29 °C in one of the hours of the experimental day. From the daily measurement obtained (Figure 3), 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 lowest. Moreover, it was observed that even though the solar radiation was highest between the hours of 1:00 pm and 2:00 pm, and the maximum distillate yield was obtained between the hours of 2:00 pm and 3:00 pm for both solar still. Figure 4 shows the variation of distillate versus time for the period of five days. This result is for the solar still with variable collector angle (still A) and a conventional single slope solar still with a rigid collector angle (still B).

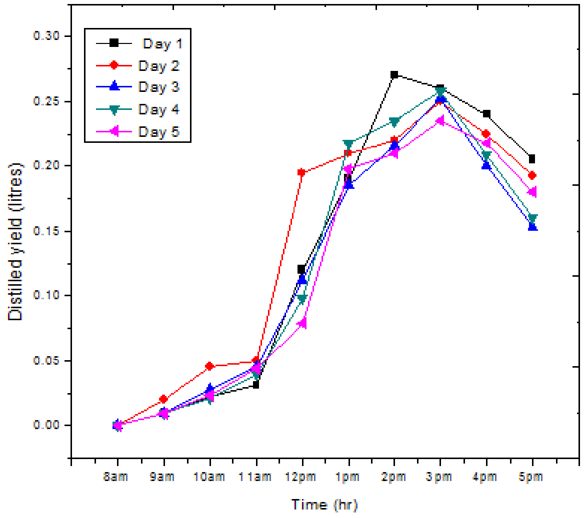


Fig. 3: Variation of distillate with respect to time of the day for solar still A.

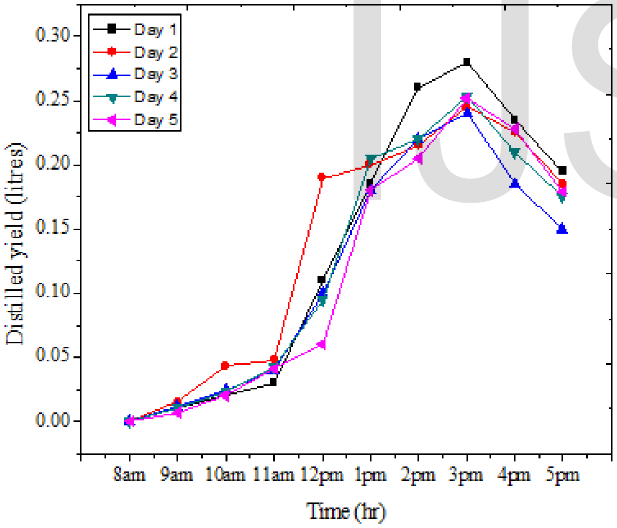


Fig. 4: Variation of distillate with respect to time of the day for solar still B

Considering nine (9) sunshine hours for the experiment, the average solar radiation, and other conditions, it was observed that the modified single slope solar with variable collector angles was more efficient than the conventional single slope solar still (Figure 6). The former had a yield of 1.407 liters/day/m² while the later had 1.366 liters/day/m² (Figure 5). Also, Figure 6 clearly shows that, the still A has a higher efficiency (42 %) than still B (39 %). This can be explained based on the ability of the later to have higher optimal solar radiation at any given time due to its variable collector angle.

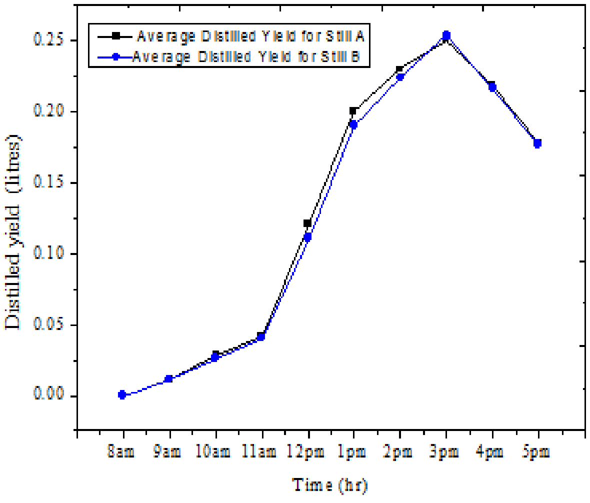


Fig. 5: Average distillate with respect to time.

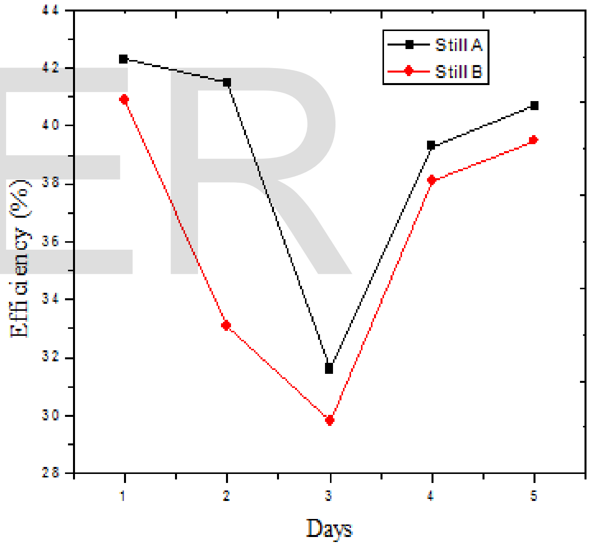


Fig. 6: Efficiency of still with respect to time

### 5.2 Statistical Analysis

A paired T-test was applied using Minitab software package (Minitab Model 15, Princeton, New Jersey, USA) as illustrated in Table 4. The result revealed that, there was no significant difference in hypothetical mean of the distillate between the two stills. A probability value of 0.058 was recorded at 95% confidence interval (CI). This value obtained is greater than the significance value of 0.05; hence not enough evidence to reject the null hypothesis ($H_o$). Also, a T-value of 2.17 lies within the critical region of the 95% CI as illustrated in Figure 8. Moreover, as illustrated in Figure 7, $H_o$ lies within the mean range of the boxplot and this implies that, there is no difference in the mean of the distillate between the two stills. Furthermore, sequential analysis of variance as illustrated in Tables 5 and 6 clearly shows that both stills exhibited a quadratic regression. The p-values of 0.133 and 0.177 respectively for stills A and B are far greater than the significance level of 0.05. From the above analysis, there was not enough evidence to reject $H_o$ and it is concluded that, there is no significance difference in the mean of distilled yield between the two stills.

Table 4: Paired T-Test for Distilled Yield at 95% CI

| | N | Mean | StDev | SE Mean |
|---|---|---|---|---|
| **Still A(hrs)** | 10 | 0.1279 | 0.0994 | 0.0314 |
| **Still B(hrs)** | 10 | 0.1250 | 0.0986 | 0.0312 |
| **Difference** | 10 | 0.00296 | 0.00431 | 0.00136 |

T-Test of mean difference = 0 (vs not = 0): T-Value = 2.17 P-Value = 0.058

Table 5: Sequential Analysis of Variance for Still A

| Source | DF | SS | F | P |
|---|---|---|---|---|
| **Linear** | 1 | 0.0700569 | 29.84 | 0.001 |
| **Quadratic** | 1 | 0.0054812 | 2.89 | 0.133 |
| **Cubic** | 1 | 0.0116909 | 43.62 | 0.001 |

Table 6: Sequential Analysis of Variance for Still B

| Source | DF | SS | F | P |
|---|---|---|---|---|
| **Linear** | 1 | 0.098124 | 31.56 | 0.000 |
| **Quadratic** | 1 | 0.0043850 | 2.31 | 0.173 |
| **Cubic** | 1 | 0.0118225 | 47.59 | 0.000 |

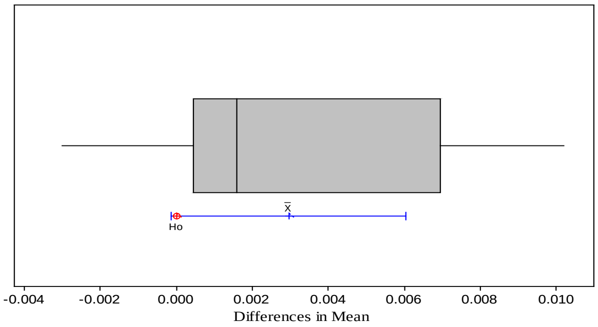


Fig. 7: A Boxplot showing differences in mean for still A and still B at 95% CI

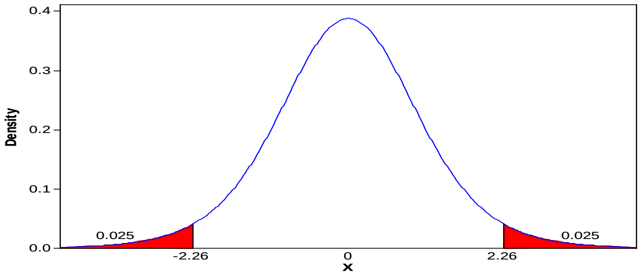


Fig. 8: Probability distribution plot at $\alpha = 0.05$ for T-test

A paired T-test was applied using Minitab software package (Minitab Model 15)

## 5.3 Cost Evaluation of the Solar Stills

Table 7 highlights the cost incurred in the fabrication of the two solar stills. A total cost of $193 was used to construct both solar stills. This implies that a total of $96 is needed to build a modified single solar still with variable collector angle. The implication of this is for the development of a cost effective single solar stills that is relevant in any geographical location.

Table 7: Cost estimation for the fabrication of two solar stills (Still A and B)

| S/N | Materials | Quantity | Dimension (mm) or Weight (g) | Cost/Dimension ($) | Total Cost ($) |
|---|---|---|---|---|---|
| **1** | Plywood | 4 | 2000 x 1000 x 10 | 16 | 64 |
| **2** | Glass | 2 | 760 x 670 | 13 | 13 |
| **3** | Wood | 1 | 1200 x 1000 x 40 | 10 | 10 |
| **4** | Fiber glass | 1 | 2000 x 1000 x 30 | 9 | 9 |
| **5** | Araldite | 2 | 60 | 3 | 6 |
| **6** | Putty | 1 | 2000 | 2 | 2 |
| **7** | Nail | 1 | 6000 | 3 | 3 |
| **8** | Paint | 1 | N/A | 4 | 4 |
| **9** | Aluminum plate | 2 | 760 x 660 | 20 | 40 |
| **10** | Aluminum foil | 1 | 2000 x 1000 x 1 | 2 | 2 |
| **11** | Labor | 2 | - | 20 | 40 |
| **Total Cost incurred** | | | | | **193** |

## 6.0 SUMMARY AND CONCLUDING REMARKS

This work has explored the design of a cost effective, flexible and robust single solar still with variable collector angle. A modified single slope solar still was designed, fabricated and experimentally tested during daytime for the period of nine (9) sunshine hours in five (5) days. A positive control, still B (with rigid collector/inclination angle) and a modified solar still, still A (with variable collector angles) were tested under outdoors of Samaru, Zaria climatic conditions. It was found over the hours of testing, that the daily distillate produced was 1.407 liter/day/m$^2$ and 1.366 liter/day/m$^2$ for stills A and B, respectively. A sample efficiency of 42 % and 39 % for still A and still B was recorded in the second day.

Statistical analysis was also used to discuss the distillate as well as the efficiency obtained for both solar stills. A paired T-test revealed that, there was no significant difference in hypothetical means of the distillate obtained between the two stills. Although there are slight differences in the distillate obtained and efficiencies, it cannot be ruled out that, the performance of still A is better than still B when different locations are considered. Furthermore, the total unit cost in fabricating a modified single solar still with a variable collecter angle was as low as $96.00. This still can be used effectively irrespectively of the geographical location.

The implications of the results from the design are for the development of a robust and dynamic single slope solar still system with variable collector/inclination angle. This has the potential and capacity to produce distilled water for domestic, industrial and commercial purposes irrespective of the geographical location.

## ACKNOWLEDGMENTS

The authors are thankful to the department of Mechanical Engineering, Ahamadu Bello University (ABU), Zaria and the African University of Science and Technology (AUST) for their invaluable supports.

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