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Experimental Investigation Of The Performance Of Basin Type Single-Slope Solar Still

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Abstract: The supply of drinking water is a growing problem especially for developing countries. Solar stills have been considered as one of the viable options of converting brackish or dirty water into distil water. Basin water depth is one of the design and operating parameters that determines the performance of solar still. Therefore, three identical simple basin single slope solar stills A, B, and C were constructed and their performance was experimentally investigated under the same conditions at basin water depths of 5mm, 10mm and 20mm respectively. The distillate productivity, solar intensity, and the temperatures of the basin water, glass cover and the ambient of the three stills were measured and their relationships were investigated. The heat losses as well as the experimental and thermal efficiencies of the stills were estimated. The results reveal that still A demonstrates high performance followed by still B. This however indicates that the performance of a solar still is high at lower basin water depths.

Index terms: Performance, Solar still, Experiment, Productivity, Efficiency, Heat losses

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Nomenclature

$q_{ewg}, q_{rwg}, q_{cwg}$ = Evap, rad and convective Hear transfer from water to glass, W

q_{rga}, q_{cga} = Radiative and convective heat transfer from glass to atmosphere, W

q_b =Heat loss from basin to ground and Periphery,W

$h_{ewg}, h_{cwg}, h_{rwg}$ = Evap, convective and Radiative heat transfer coefficient from Water to glass

h_{cga}, h_{rga} = Convective and radiative heat Transfer coefficient from glass to ambient

α_w, α_g = Absorptivity of water and glass

C_w, C_g = Heat capacity of water and glass

T_w, T_g, T_a, T_s = Temperatures of water, glass, Ambient and sky, K

F = Shape factor

σ = Stefan Boltzmann constant

I = Solar insolation W/m^2

P_w = Saturation partial pressures of water and Vapour at water temperature,

P_g = Saturation partial pressures of water and Vapour at glass temperature

ε_g = Emissivity of glass

η_{exp}, η_{th} = Experimental and thermal efficie-ncies of the stills, %

A_w, A_g = Basin water and glass cover surface Areas, m2

L_w = Latent heat of evaporation of water

Introduction

Water and energy are the two basic elements that influence the quality of civilized life. Fresh water is the fundamental life source on earth. Today, fresh water demand is increasing continuously because of the industrial development, intensified agriculture, improvement of standard of life and increase of the world population. Only about 3% of the world water is potable and this amount is not evenly distributed on earth. [1][2] The supply of drinking water is a growing problem for most parts of the world. More than 80 countries, which between them have 40% of the world's population, are being suffered from this problem [1]. Over one billion people each year are exposed to unsafe drinking water due to poor source water quality and lack of adequate water treatment. This results in 900 million cases of diarrhea each year.[3] Studies have shown that every 0.5% of those exposed to unsafe drinking water still die from diseases carried by the contaminated water: another 0.25% will also die from dehydration due to diarrhea.[4] There are many ways of getting fresh water from dirty or brackish water. Some of these include boiling, freezing, using vapour compression plant, electrodialysis, use of solar stills, etc. [5] Although, many of these techniques require low initial investment than the solar stills, some of the techniques are associated by heavy running and maintenance costs while the use of others have negative impact on the environment. The use of solar stills for the distillation of dirty and brackish water is a viable option especially in hot and dry have climates. Studies have shown that there is high degree of disinfection of contaminated water using solar energy. This is as a result of the photogenic inactivation of the

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microbial loads in the contaminated water.[6][7] The most common type of solar still in use today is the basin type. Some of the basin type solar stills designs are: double sloped symmetrical still with continuous basin, double slope symmetrical still with basin divided into two bays, solar still with single slope and a continuous basin, unsymmetrical double sloped still with divided basin, v-trough type solar still, solar still with plastic inflated cover, solar still with stretched plastic film and divided basin.[8] The distillate output from a solar still depends on many parameters like climatic parameters such as solar Insolation, ambient air temperature, wind speed, atmospheric humidity, sky conditions etc and design parameters such as thermophysical properties of the material use in its construction, orientation of still, tilt angle of cover, spacing between cover and water surface, insulation of the base, vapour tightness, absorptance-transmittance properties of still, etc and operating parameters such as water depth in the basin, initial water temperature, water salinity, etc. [8] This paper is therefore an attempt to experimentally investigate the performance of a basin type single slope solar still at different water depths in the basin under the prevailing weather condition in Bauchi, Nigeria.

Principles of Solar Still

Solar radiation after transmission through the transparent cover is absorbed by water in the basin, thereby raising water temperature compared to that of the cover. The water now losses water by evaporation, convection, and radiation to the cover and by conduction through the base and edges of the still. The evaporated water from the basin increases the moisture content in the enclosure which finally condenses on the underside of the cover, slips down into the condensate channels and through them out of this still for use. The schematic diagram and the sectional view of the solar still are shown in figures 1 and 2 respectively.

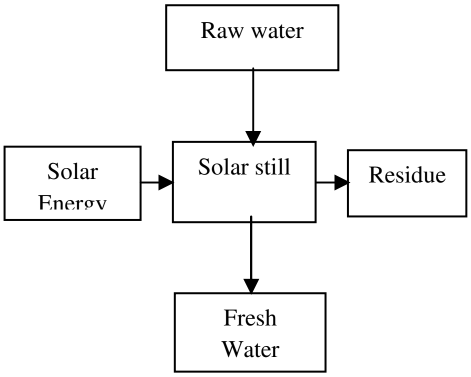

Figure 1 Schematic of Solar Distillation Process

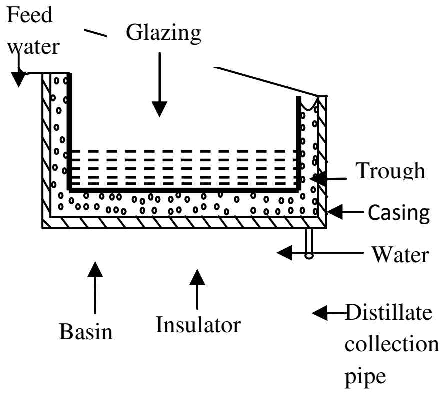

Figure 2 Sectional View of the Single-slope Solar Still

Thermal Analysis of the Solar Still

The operation of solar still is governed by the various heat and mass transfer modes occurring in the system. The major energy transport mechanism in the still is shown in figure 3.

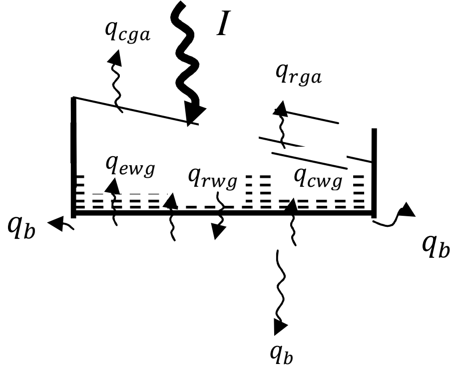

Figure 3 Energy Transport Mechanism in the still

A single basin solar still energy flow and energy balance equations for the different components can be expressed as follows:[9][8]

Heat Balance for Water in the Basin

The instantaneous heat balance equation on the basin water is given by equation 1.

$$I\alpha_w\tau = q_{ewg} + q_{rwg} + q_b + C_w\frac{dT_w}{dt} \quad (1)$$

Heat Balance for the Glazing Cover

The heat balance for the glazing cover is given by equation 2. [8]

$$q_{ga} + C_g\frac{dT_g}{dt} = I\alpha_g + q_{ewg} + q_{rwg} + q_{cwg} \quad (2)$$

Where $q_{ga} = \left(= q_{cga} + q_{rga}\right)$ is the heat loss from the glass cover to atmosphere.

Total Heat Balance on the Still

The total heat balance on the still is expressed by 3[8] as:

$$I\alpha_w\tau + I\alpha_g = q_{rga} + q_b + C_g\frac{dT_g}{dt} + C_w\frac{dT_w}{dt} \quad (3)$$

The heat transfer by radiation, q_{rwg}, from water surface to glass cover can be calculated using equation 4. [8] The heat transfer by radiation, q_{rwg}, from water surface to glass cover can be calculated from equation 4.0.

$$q_{rwg} = h_{rwg}(T_w - T_g) \quad (4)$$

Where h_{rwg} is the radiative heat transfer coefficient which is given by as: [2]

$$h_{rwg} = \varepsilon_f\sigma\left(\frac{T_w^4 - T_g^4}{T_w - T_g}\right) \quad (5)$$

Where ε_f is the effective emissivity factor of diffuse radiation from the water surface to the glass cover. Equation 6 can then be expressed as: [2]

$$q_{rwg} = F\sigma(T_w^4 - T_g^4) \quad (6)$$

Where F is the shape factor which depends on the geometry and the emissivities of water and glass cover. For the basin type solar still and for low tilt angles of glass cover, the basin and glass cover can be assumed to be parallel infinite plates. [2] The shape factor can be assumed to be equal to the emissivity of the water surface which is 0.9. Hence equation 7 can be expressed as: [2]

$$q_{rwg} = 0.9\sigma(T_w^4 - T_w^4) \quad (7)$$

The convective heat loss from hot water surface in the still to the glass cover can be calculated from equation 8.

$$q_{cwg} = h_{cwg}(T_w - T_w) \quad (8)$$

Where h_{cwg} is the convective heat transfer coefficient. Dunkle (1961), suggested equation 9 to be an empirical relation for the convective heat transfer coefficient.

$$h_{cwg} = 0.884\left[T_w - T_g + \frac{(P_w - P_g)}{268.9 \times 10^3}T_w\right]^{1/3} \quad (9)$$

Where P_w and P_g are the saturation partial pressures of water vapour (N/m2) at water and glass temperatures respectively; which are given by equations 10 and 11.[11]

$$P_w = \exp\left[25.31 - \left(\frac{5144}{T_w}\right)\right] \quad (10)$$

$$P_w = \exp\left[25.31 - \left(\frac{5144}{T_w}\right)\right] \quad (11)$$

The evaporative heat loss q_{ewg} from water surface to glass cover is calculated from equation 12. [2]

$$q_{ewg} = h_{ewg}A_w(T_w - T_g) \quad (12)$$

Where h_{ewg} is the evaporative heat transfer coefficient and is expressed as: [2]

$$h_{ewg} = 16.273 \times 10^{-3}h_{cwg}\left(\frac{P_w - P_g}{T_w - T_g}\right)L_w \quad (13)$$

But the empirical relation of q_{ewg} as given by Dunkle (1961) is:

$$q_{ewg} = 16.28 \times A_w h_{cwg}(P_w - P_g) \quad (14)$$

Heat loss through the ground and periphery q_b is difficult to compute since the soil temperature is unknown. Moreover, the heat conducted in the soil during the daytime comes back in the basin during the night time. However, it can be computed using equation 15.[2]

$$q_b = \cup_b(T_w - T_g) \quad (15)$$

Where $\cup_b$ is the overall heat transfer coefficient from bottom of the basin to the ground. Cooper (1973) conducted careful experiments and determined a value of $\cup_b$ varying from 2.8W/m2 to 1.7W/m2. The convective heat loss q_{cga} from glass cover to ambient air can be calculated from equation 16.

$$q_{cga} = h_{cga}(T_g - T_a) \quad (16)$$

Where h_{cga} is the convection heat transfer coefficient and is expressed by equation 17.

$$h_{cga} = 2.8 + 3.8V \quad (17)$$

Where V is the wind speed in m/s. The radiation heat loss q_{rga} from glass to sky can be determined provided the radiant sky temperature T_s is known, which very much depends on atmospheric conditions such as the presence of clouds etc. Generally for practical purposes the average sky temperature T_s can be assumed to be about 12K below ambient temperature, i.e $T_s = T_a - 12$ [8] or it can be determined from equation 18. [2]

$$T_s = 0.0552T_a^{1.5} \quad (18)$$

Therefore, the radiative heat loss from glass cover to the atmosphere is given by equation 19. [8]

$$q_{rga} = \varepsilon_g\sigma(T_g^4 - T_s^4) \quad (19)$$

Materials and Methods

Experimental investigation of the performance of the single slope solar still of basin type was carried out under the prevalent weather condition of the test day in Bauchi, Nigeria (Lat. 100 17' Long. 9047') in June 2004. Three identical stills labeled still A, still B and still C, were filed with water at depths of 5mm, 10mm and 20mm above the basin respectively. The basins of the stills measure 260cm2 and 12cm deep were made of steel plates and are coated with black non-toxic paint to enhance their absorptance and also to yield optimum result in terms of microbial destruction. The basins of the stills were insulated with wood sawdust. The transparent covers of the stills were made of glass of transmittance 90%. The sectional view of one of the solar stills is shown in figure 2.0.

Experimental Method

The three solar stills (still A, still B, and still C) were placed in the sun with their glass covers inclined at 10.30 to the sun. The angle is Bauchi town location's latitude. The three stills, A,B and C, were filled with water to depths of 5mm, 10mm and 20mm respectively, with the units oriented towards the sun. The data was recorded t one hour interval from 9.00am to 18.00pm local time on the test day. The raw water used was gotten from a well in Bauchi Central Area. Thermocouples were used to measure the temperatures of various points on the stills. The outputs of the thermocouples were monitored on Tomsway electronic digital readout. The hourly insolation on the location of test was determined by the aid of frosted glass solarimeter. The distillate output from the stills was collected in 500ml measuring cylinders. The value of the average wind speed on the test day was gotten from World Meteorological Organization. [13]

Determination of the Efficiencies of the Stills

Experimental efficiency

The experimental steady state efficiency (η_{ep}) of the stills is calculated using equation 20. [2]

$$\eta_{ep} = \frac{mL_w}{IA_g\Delta t} \qquad (20)$$

Where m, L_w, A_g and Δt are mass condensate collected in a time interval, water latent heat of evaporation, hourly solar radiation flux, the glass collecting area and the time interval respectively. The daily experimental efficiency $(\eta_{ep(d)})$ of the stills are determined using equation 21.[14]

$$\eta_{ep(d)} = \frac{\sum m \times L_w}{\sum I \times A \times t} \qquad (21)$$

Thermal efficiency

In calculating the thermal efficiencies of the stills, the pertinent heat transfer coefficients were analyzed and the average temperatures of the basin water and the glass covers were used. The thermal efficiencies of the stills are calculated using equation 22. [15]

$$\eta_{th} = \frac{\alpha_w \tau_g h_{ewg}}{h_{ewg} + h_{cwg}} \qquad (22)$$

The computed values of the thermal efficiencies of the stills are presented in Table 5.

Results and Discussion

Table 1 Experimental Temperature Distribution for Still A

Time (hr)	Tw (K)	Tg (K)	Ta (K)	I (W/m2)	Yield (ml)
9.00	302	301	300	711.36	Trace
10.00	302	302	301	718.21	Trace
11.00	312	304	301	725.04	8
12.00	318	306	302	738.72	23
13.00	323	312	304	766.08	52
14.00	328	314	305	875.52	88
15.00	328	313	305	861.84	172
16.00	325	311	305	848.16	213
17.00	316	306	304	807.12	281
18.00	310	305	304	759.24	304
Ave/ Total	316.4	307.4	303.1	781.13	1141

Table 2 Experimental Temperature Distribution for Still B

Time (hr)	Tw (K)	Tg (K)	Ta (K)	I (W/m2)	Yield (ml)
9.00	302	303	300	711.36	Trace
10.00	302	306	301	718.21	Trace
11.00	312	307	301	725.04	Trace
12.00	318	312	302	738.72	7
13.00	323	314	304	766.08	18
14.00	328	315	305	875.52	47
15.00	328	313	305	861.84	75
16.00	325	312	305	848.16	151
17.00	316	311	304	807.12	187
18.00	310	308	304	759.24	273
Ave/ Total	316.4	310.1	303.1	781.13	758

Table 3 Experimental Temperature Distribution for Still C

Time (hr)	Tw (K)	Tg (K)	Ta (K)	I (W/m2)	Yield (ml)
9.00	300	303	300	711.36	Trace
10.00	302	307	301	718.21	Trace
11.00	303	307	301	725.04	Trace
12.00	306	309	302	738.72	Trace
13.00	310	309	304	766.08	Trace
14.00	319	312	305	875.52	6
15.00	323	315	305	861.84	17
16.00	323	314	305	848.16	48
17.00	321	310	304	807.12	81
18.00	318	307	304	759.24	153
Ave/ Total	312.7	309.3	303.1	781.13	305

Table 4 Hourly Condensate Collected from the Stills (kg/m^2)

Time (hr)	Still A	Still B	Still C
9.00	-	-	-
10.00	-	-	-
11.00	0.3	-	-
12.00	0.88	0.26	-
13.00	2	0.69	-
14.00	3.33	1.8	0.23
15.00	6.6	2.88	0.65
16.00	8.18	5.8	1.84
17.00	10.78	7.18	3.1
18.00	11.66	10.48	5.87
Ave/ Total	43.78	29.09	11.69

Table 5 Computed Values of Heat Losses from the Stills

Time (hr)	Still A	Still B	Still C
q_{cwg} (W)	0.36	0.14	0.1
q_{ewg} (W)	2080	807.2	552.2
q_{rwg} (W)	1.45	0.71	0.54
q_{cga} (W)	1.67	2.33	2.41
q_{rga} (W)	1.67	1.67	1.67
Total	2085.15	812.05	556.92

Table 6 Efficiency of the Stills

Time (hr)	Still A	Still B	Still C
Experimental (%)	35	23.3	9.4
Theoretical (%)	72	72	72

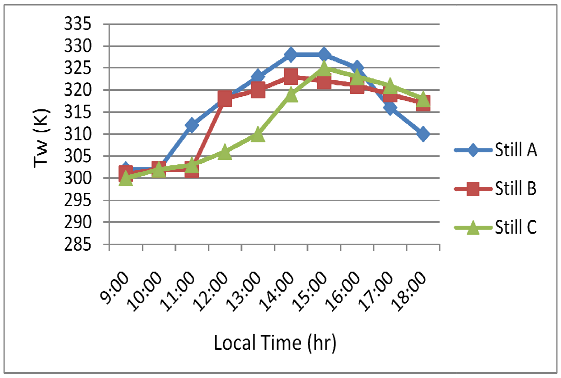

Figure 4 Basin Water Temperature Vs Time of the Day

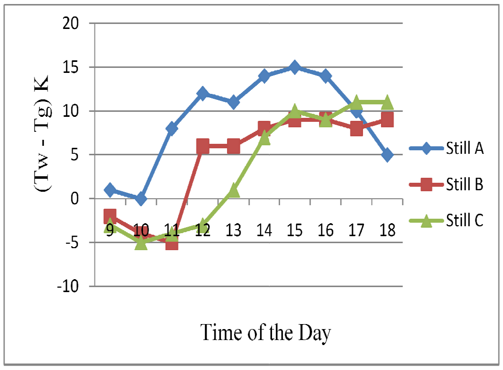

Figure 5 Plot of $(T_w - T_g)$ versus Time of the Day

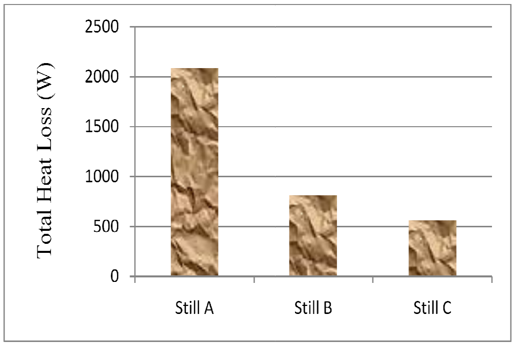

Figure 7 Heat Losses of the Stills

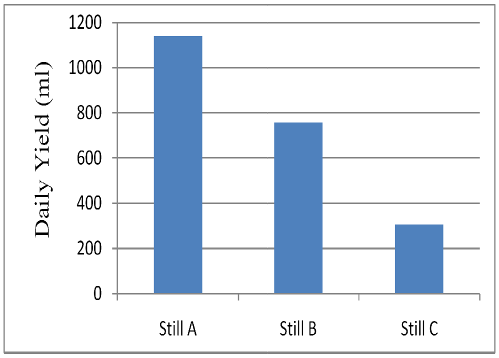

Figure 6 Daily Productivity of the Stills

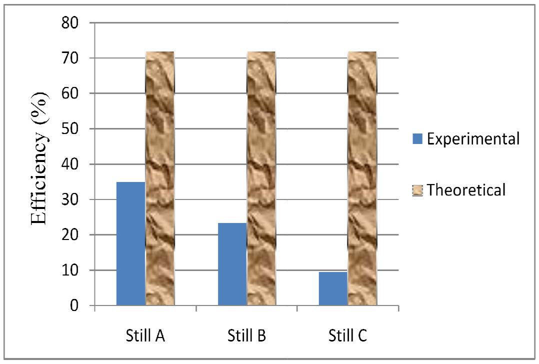

Figure 8 Efficiency of the Stills

Table 5 and figure 7 show the heat losses from the three stills A, B and C. The heat losses from stills A, B and C are 2085.15W, 812.05W and 556.92W respectively. It can be seen that the total heat loss from Still A is higher followed by still B and C. This shows that the heat loss in a solar still is a function of the basin water depth which can be attributed to the relatively higher basin water temperature for the lower water depths. Figure 4 shows that during the later periods of the test, the basin water temperature in still C is relatively higher which might be attributed to the higher volume of water in the basin which makes it to store heat for a longer period. The daily productivity of the stills A, B and C as seen from Table 4 and figure 6 are 43.78, 29.09 and 11.69 kg/m^2 respectively. This shows that the daily condensate collected from the stills varies linearly with the basin water depths. This can be attributed to the fact that the lower the basin water depths, the higher will be the evaporation rate provided other factors that determine the rate of evaporation are kept constant. Table 6 and figure 8 show that the experimental efficiencies of the stills A,B and C are 35%, 23.3% and 9.4% respectively. This shows that by keeping other factors constant, the experimental efficiency of a solar still increase with the water depth. However, the thermal efficiency of the three stills is 72% meaning that thermal efficiency of solar still for any range of basin and glass cover temperature is the same. Figure 4 shows the plot of basin water temperature as a function of time of the day. This indicates that for all the stills, the basin water temperature rises as time progresses and reaches its peak in the afternoon and then declines. This can be attributed to the changes in solar intensity with time of the day as can be seen in Tables 1, 2 and 3.

Conclusion

The performance of a simple basin single slope solar still at different basin water depths was experimentally investigated. Still A that has a basin water depth of 5mm has the greater distillate productivity of 43.78 kg/m^2 per day compares with still B and C that have daily productivity of 29.09 and 11.69 kg/m^2. Keeping the basin water depth of a single slope solar still low will enhanced the performance of such still. Therefore, amelioration of the output of solar still can be achieved by the use of lower basin water depth.

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