International Journal of Advances in Scientific Research and Engineering (ijasre)

E-ISSN : 2454-8006

DOI: 10.31695/IJASRE.2023.9.7.9

Volume 9, Issue 7
July - 2023

Analysis of Solar Distillation System for Clean Water Distribution : A Review

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ABSTRACT

Different solar stills technologies is widely reviewed to digest their pros and cons. Solar still is a natural phenomenon of purifying sea and brackish water to provide affordable and reliable potable water. For the technology to be sustainable and utilised on a large scale, productivity needs to be improved. The factors that contribute to the performance of a still were highlighted and analysed. And the energy and mass balance that takes place in solar still was expressed and defined by different researchers. The efficiency of a still is determined by the temperature variation of the evaporated water in the basin and the outside temperature of the glass cover. The insulation material plays a vital role in the prevention of heat loss and conservation of heat energy to increase the overnight yield when solar energy is not available.

Keywords: Clean Water Distribution, Design, Distillation, Distribution, Solar Energy.

1.0 INTRODUCTION

Statistically 2.7 billion people worldwide are directly or indirectly affected by the lack of affordable potable drinking water. Also, by 2025, the number may rise to more than 5 billion due to climate change and the dramatic increases in the World population. Most of the Areas affected by drought have inhabitants with high poverty rates which makes their situations worsen with the non-availability of potable water [1]. However, access to brackish groundwater and seawater allows solar distillation systems to provide a clean and affordable source of potable water supply to rural communities, especially in Africa [2].

Solar distillation system is a solar thermal process that mimics the hydrological cycle of the earth and it offers a solution for potable water supply to rural households [3]. In the operation of solar distillation, clean water is evaporated and condenses on the transparent glass cover of a still (inclined to allow drift of clean water flow), as a result of the temperature variation between it and the pure water into a collector. The impurities in the form of brine are left on the floor or basin liner of the still [3] & [4].

The solar still systems are classified as active and passive. The active type uses external sources to influence the evaporation and condensation rates for the potable water supply. Whereas, the passive system is the conventional still that depends on the natural phenomenon of solar thermal energy to provide the production of pure water[5].

The performance of solar still is affected by the following parameters; inclination angle of the glass cover, water depth of the basin, the material of the basin, insulation material, wind velocity, ambient temperature and solar radiation. The yield of a solar still is determined by the difference between the temperature of water in the still and the temperature on the glass cover [2]&[5].

This paper investigates and analyses various passive and active solar distillations to design efficient solar still to provide a clean and affordable water supply for the rural populace. This research aims to review different methodologies that are viable, and practicable.

2.0 METHODOLOGY

An analysis of various solar still designs was carried out to improve the supply of clean and affordable potable water. A methodology was adopted, which involves reviews of different solar still designs to sustain and boost the efficiency of the still. In the review process, certain parameters are considered as follows; the inclined angle of the glass cover, water depth of the basin, insulation material used in the construction of the still, water temperature inside the basin, inside glass cover temperature, ambient temperature, wind velocity, solar radiation. And the energy and mass balance of the solar still.

2.1 Types of solar still designs

2.1.1 Conventional basin solar still

The solar still design is made of a wooden box as the outside cover with a dimension of 2200 mm by 1200 mm. The sidewall is slanted at an angle of 10.4 with a height of 380 mm at the rear and a height of 200 mm at the front of the solar still. The inside of the solar still is made of Galvanised iron sheet shaped into a wooden box with the dimension of 2000 mm by 1000 mm at the base and height of 380 at the rear and 200 mm at the front and painted black to facilitate heat from the solar radiation. The top is covered with transparent glass, slanted to the inclined angle. Saline or brackish water is poured into the still to fill it to a predetermined level and then exposed to solar radiation [2].

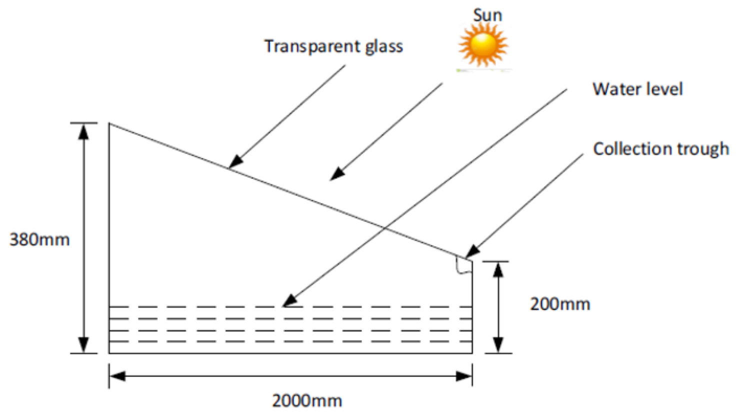

Figure 1: Conventional solar still [2].

The glass cover permits solar radiation to get into the still, which is absorbed predominantly by the black base. Consequently, the water gets heated up and hence there is an increase of hot moist air that occurred between the water surface and the glass bottom level. The bottom also radiates energy in the infrared region which is mainly absorbed by water in the basin. Thus, the glass cover traps the solar energy inside the still. It also reduces convective heat losses. The glass cover is usually sloped to enable the water vapour which condenses on the interior surface to trickle into a collecting trough/ catch basin. The area of the still is 2 m², with an inclination of 10.4° (based on the latitude of Bauchi, Nigeria), the orientation of north to south [2].

The still consist of three essential components: (a) a Basin made of galvanised iron and painted black, in which the contaminated water is con-fined, (b) A transparent glass pane of 4 mm thickness which covers the still and vapour condenses from the feed water; (c) A catch basin, which collected the distilled water into the storage tank [2].

2.1.2 Greenhouse solar still

This type of solar still generally imitates a part of the natural hydrologic cycle in that the Sun's rays heat the saline water so that the production of water vapour (humidification) increases. The water vapour is then condensed on a cool surface, and the condensate is collected as a freshwater product. In the greenhouse solar still, saline water is heated in a basin on the floor, and the water vapour condenses on the sloping glass roof that covers the basin, as shown in Figure 2 [6]& [7].

DOI: 10.31695/IJASRE.2023.9.7.9

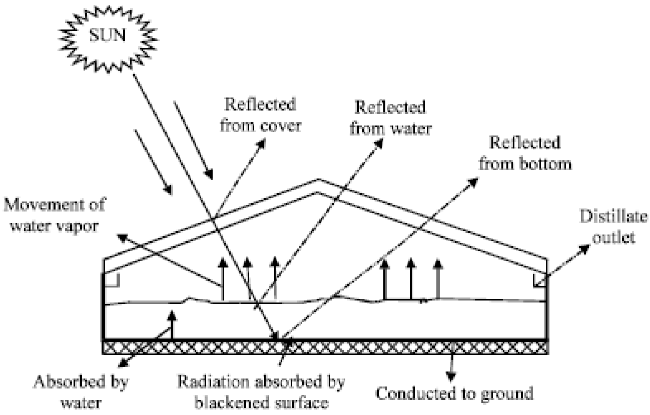

Figure 2: Greenhouse solar still [6]

2.1.3 V –shape glass envelope solar still

A V-shape glass envelope solar still with double inclined glass produces more water potable compared to the single slope solar still [3]. The difference in temperature between the lower part of the glass inside the still and the water temperature in the basin determines the rate of condensation on the glass cover and invariably controls the output of potable water produced by the still. To improve the rate of condensation in the still, an external reflector is used as an attachment to the still or application of dye mixed with water in the basin [4].

The still is painted black inside and outside to increase the rate of absorption of solar radiation. For insulation, plywood is used as a cover and to reduce heat loss. A wooden case is used as a thermal insulator to reduce the heat. The top cover of the still is made of glass and the glass covers are tilted at an angle of 2º towards the centre of the still to minimise air leakage and for smooth outward flow of distilled water [4]&[8].

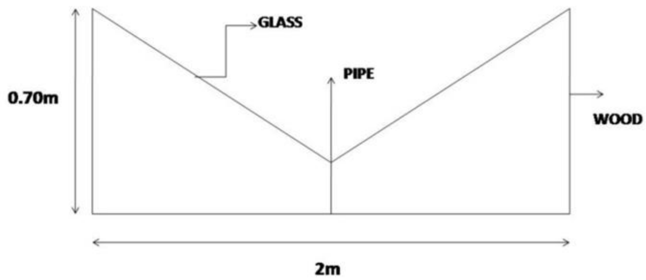

Figure 3: V shape solar still [9]

The efficiency of solar still can be determined by the energy used in vapourising the water contained in the still over the incident solar energy on the glass cover [4]&[10].

2.1.4 Wick solar still

The operation of a wick solar still is similar to the conventional solar still, the only difference is that energy used for heating flows through the wick by capillary action. A lot of heat developed in the still and the heat transfer process starts from the wick surface to the glass cover towards the ambient air. The water on the surface of the wick is heated and evaporated as water vapour, then moves to the lower surface of the glass. The water condensed and form droplet that slide to the collecting trough/ drainage channel [11].

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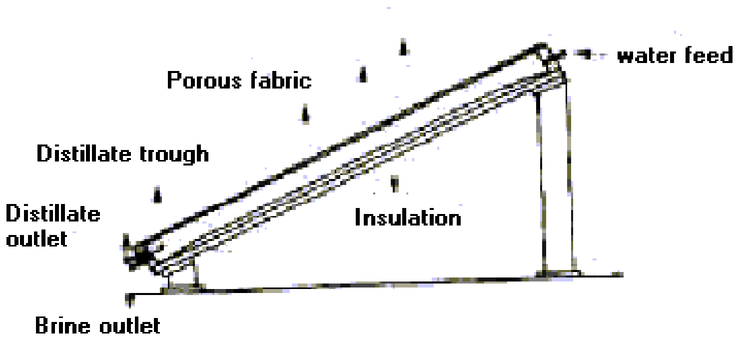

Figure 4: Tilted wick solar still [11]

3.0 Factors Affecting Solar Still Performance

3.1 Climatic conditions (Solar radiation and Wind speed)
The availability of solar radiation with high intensity increases the production of potable water. In the afternoon highest production is recorded, when the solar radiation is at its peak. Also, wind speed has a tremendous effect on the performance of the still. The wind speed reduces the temperature of the top cover of the glass cover due to convective heat transfer. As a result the productivity of the still increases [12].

3.2 Basin water depth
The effect of basin water depth on the productivity of the still has been investigated by many researchers. This factor is the most important because evaporation is high when the water depth is low [13]. Tiwari, Sumegha and Yadav [14] examined the effect of seven different depths of basin water (0.02 m, 0.04 m, 0.06 m, 0.08 m, 0.10 m, 0.12 m and 0.14 m). The productivity of the still was high when the water depth is 0.02 m and low at a water depth of 0.14 m. Elango and Murugavel [15] investigated the effect of water depth on the single and double basins, at different water basin depths. The output in both scenarios shows the same trend. Rajamanickam and Ragupathy [16] investigated the influence of water depth on solar stills and the outcome gives the same results.

3.3 Slope of the cover
The slope of the solar still cover was observed to improve the productivity of the solar still It is observed that the slope of the cover of the solar still directly affects its productivity [17]. The suitable angle of inclination of the glass cover provides adequate solar radiation into the still and improved the flow of water droplets on the glass cover to the collection channel[18].

Khalifa and Mahmood [19] found out that different angles of inclination of the glass cover of the still could improve the efficiency by 63%. Bilal et al. and Velmurugan et al. [20]&[21] respectively found that setting the inclination angle of the glass cover of a still to the corresponding latitude of a particular geographical location improved the output of the solar still effectively and the solar radiation intensity into the still basin.

3.4 Thickness of the cover
The capability of glass to transmit high-frequency radiation using selective transmissivity and retard low-frequency, these attributes make it a perfect material for solar still cover [22]& [23]. Research conducted by Ghoneyem and Ileri [24] shows that varying the glass cover thickness by 3, 5 and 6 mm respectively. 3 mm thick glass cover, perform better with the highest output. However, a very thin glass thickness has a low condensation rate. Glass cover with 3–5 mm thickness perform optimally [25]&[26].

3.5 Material of the cover
Previously the issue related to the transmissivity of a glass cover is a very important parameter. Also, the thermal conductivity of the glass cover improved the output of the solar still. Some researcher has studied the performance of three different material used as cover for solar still namely; glass, copper and plastic. Copper was found to produce a higher yield and while plastic produce the least [23]. For cost effective and since most solar still are used in the rural area, glass is predominately used as a cover material because of affordability.

3.6 Water–glass cover temperature difference
The temperature difference between water and glass cover influences the yield of solar still. Various researchers proved the narrative to be true by cooling the top of the glass and recording a 6% increase in the output [27], whereas, the cooling film was used on the glass cover with a 20% increase [28]. Others increased the temperature of the water using water heaters and electric

DOI: 10.31695/IJASRE.2023.9.7.9

resistance heaters observed tremendous improvement in the yield of the still [29]&[30]. Consequently, the higher the difference between the water–glass cover temperature, the higher the output of the still.

3.7 Insulation material and thickness

As the solar radiation energy is absorbed in the solar still during the day, excess energy could be lost through the bottom basin liner and side walls as waste heat. Proper insulation material and thickness are needed to avoid loss. Studies have been carried out to determine the effect of insulation in a solar still. It was found that the solar still with insulation produces more yield compared with the non-insulation solar still [31]&[32].

Many researchers have used Styrofoam, Polyurethane, and wooden boxes with sawdust as insulation material with remarkable success [33]. Khalifa and Hamood [34] found out that increasing insulation thickness can improve the efficiency of a still by 80%. The efficiency of solar still can be improved by up to 80% if the insulation thickness is from 3 cm to 6 cm [35]. Based on these solar still should be properly insulated with the appropriate material to reduce heat loss from the baseliner and side walls.

3.8 Surface area of evaporation

Various works of literature reported that the productivity of a solar still depends on the surface area exposed to water in the basin to increase the rate of evaporation [36].

Consequently, an increase in surface area means more absorber area that is exposed to direct sunlight, hence more increase in the temperature of the water.

4.0 ENERGY AND MASS BALANCE METHOD

The performance of a solar still is generally expressed in terms of the quantity of water evaporated per unit area of the basin in one day (cubic meters of water per square meter of the basin area per day). This performance of a solar still can be predicted by writing the energy and mass balance equations on the various components of the solar still as shown in Figure 5.

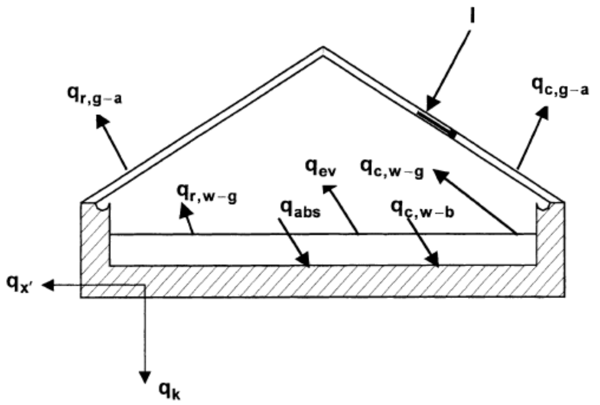

Figure 5: Energy balance of a double basin solar still [12]

The energy balances for the different components of the solar still are as follows:

4.1 Glass cover

The energy balance for the glass cover can be expressed as follows [37]:

$\tau_1 H_S + [\dot{q}_{rw} + \dot{q}_{cw} + \dot{q}_{ew}] = \dot{q}_{rg} + \dot{q}_{cg}$ 1

H_S – solar radiation on glass cover (W/m^2°C)

$\dot{q}_{rw}$ = internal heat transfer loss by radiation from the water surface to the glass

$\dot{q}_{cw}$ = internal heat transfer loss by convention from the water surface to the glass

$\dot{q}_{ew}$ = internal heat transfer loss by evaporation

$\dot{q}_{rg}$ = external heat transfer loss by radiation from the glass surface to the ambient

$\dot{q}_{cg}$ = external heat transfer loss by convention from the glass surface to the ambient

4.2 The water content (water mass)

The energy balance for water content inside the solar still is:

$\tau_2 H_S + \dot{q}_w = M_{cw} C_w \frac{dTw}{dt} + \dot{q}_{rw} + \dot{q}_{cw} + \dot{q}_{ew}$ 2

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4.3 The basin liner

The energy balance for the basin liner of the solar still is expressed as

$$\tau_3 H_S = \dot{q}_w + \left[\dot{q}_b + \dot{q}_b\left(\frac{A_{ss}}{A}\right)\right] \quad 3$$

$\dot{q}_w$ = internal heat transfer loss from water

$\dot{q}_b$ = internal heat transfer loss from basin liner

A = still basin area (m^2)

A_{sw} – Sidewall area (m^2)

4.4 The External Heat Transfer.

(a) Top loss Coefficient

The glass thickness in most cases is very small. Therefore, the temperature in the glass is assumed uniform. The external heat transfer loss by radiation and convection from the glass cover to the ambient, $\dot{q}_g$ can be expressed as

$$\dot{q}_g = \dot{q}_{rg} + \dot{q}_{cg} \quad 4$$

$$\dot{q}_{rg} = h_{rg}(T_g + T_a) \quad 5$$

Where

$$h_{rg} = \frac{\varepsilon_g \sigma[.(T_g + 273)^4 - (T_{sky} + 273)^4]}{(T_g - T_a)} \quad 6$$

And

$$\dot{q}_{cg} = h_{cg}(T_g - T_a) \quad 7$$

Substituting equations (5) and (7) into equation (4), we get

$$\dot{q}_g = h_1(T_g - T_a) \quad 8$$

Where

$$h_1 = h_{rg} + h_{cg} \quad 9$$

h_1 is expressed empirically to include the effect of free convection and radiation from the glass cover (Ilaria et al, 2010). The expression is;

$$h_1 = 5.7 + 3.8V \qquad 0 \le V \le 5ms^{-1} \quad 10$$

Where V is the wind speed measured in ms^{-1}. The expression for a zero wind speed gives heat loss by natural convection.

(b) Bottom and side loss coefficient

The heat loss from the water in the solar still to the ambient through the thick insulation and subsequently by convection and radiation from the bottom, and sides surfaces of the basin, can be written respectively as;

$$U_b = \left[\frac{1}{h_w} + \frac{1}{h_b}\right]^{-1} = \left[\frac{1}{h_w} + \frac{1}{\frac{K_i}{L_i}} + \frac{1}{h_{cb+h_{rb}}}\right]^{-1} \quad 11$$

$$U_{sw} = U_b F_1 = \left[\frac{1}{h_w} + \frac{1}{\frac{K_i}{L_i}} + \frac{1}{h_{cb+h_{rb}}}\right]^{-1}\left(\frac{A_{ss}}{A}\right) \quad 12$$

The rate of heat loss from the basin liner to the ambient per m^2 can be written as;

$$\dot{q}_b = h_b(T_b - T_a) \quad 13$$

Where

$$h_b = \left[\frac{L_i}{K_i} + \frac{1}{h_{cb} + h_{rb}}\right]^{-1} \quad 14$$

4.5 The internal heat transfer

(b) Radiative loss coefficient

The rate of heat transfer, $\dot{q}_{rw}$ from the water surface to the glass for an infinite parallel plane is given by [38] & [37]

$$\dot{q}_{rw} = h_{rw}(T_w - T_g) \quad 15$$

Where h_{rw} is given by

$$h_{rw} = \sigma\left[\frac{(T_w+273)^2 + (T_w+273)^2}{\left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_w}\right)^{-1}}\right](T_w + T_g + 546) \quad 16$$

With

$$\varepsilon_{eff} = \left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_w} - 1\right)^{-1} \quad 17$$

DOI: 10.31695/IJASRE.2023.9.7.9

(b) Convective loss coefficient

There is heat transfer across the humid air inside the distiller unit by free convection, which is caused by the effect of buoyancy, due to density variation in the humid fluid, which occurs due to the temperature gradient in this fluid. The rate of heat transfer from the water surface to the glass cover, $\dot{q}_{cw}$ by convection in the upward direction through the humid fluid can be estimated as

$$\dot{q}_{cw} = h_{cw}(T_w - T_g) \quad 18$$

The internal convective heat transfer coefficient, h_{cw}, from heat flow from the horizontal basin (the hottest region in the still) to the water mass in the basin and vice-versa is determined from the following relations [39], [40], [37] & [38]

$$Nu = Co\,(Gr.\,Pr)^{no} \quad 19$$

Where

$$Nu = \frac{h_{cw}X_1}{K_w} \quad 20$$

$$Gr = \frac{X_1^3\rho_w^2 g\beta\Delta T^{.}}{\mu_w^2} \quad 21$$

$$Pr = \frac{C_{pw}\mu_w}{k_w} \quad 22$$

$$\Delta T' = \left[\Delta T + \frac{(P_w - P_g)(T_w - 273)}{0.2689 - P_w}\right] \quad 23$$

$$\Delta T = T_w - T_g \quad 24$$

And for normal operating temperature range, say 45°C $\Delta' T$ = 17°C, expression for Gr reduces to (Tiwari, 2004)

$Gr = 2.81\times10X_1^3$ 25

Table 3.1: values of Grashof number, Gr for various average spacing X_1

X1(m)	Gr	Co	no
0.15	0.948×	0.21	¼
0.2	10^5	0.21	¼
0.25	2.248×	0.075	⅓
	10^5		
	4.390×		

Source: (Tiwari, 2004)

As can be seen from equation (25) (Gr) depends on X_1 (Table 3.1). This Table gives the value of Gr for different X_1.

The value of Pr remains constant and, as given by equation (22). For the normal operating temperature range and at spacing, X_1 = 0.25m; the value of the constant Co is: - Co = 0.075 and $n_o = \frac{1}{3}$. After substituting for the expressions of Nu, Gr and Pr in equation (19), the convective heat transfer coefficient h_{cw} becomes

$$h_{cw} = \frac{C_o K_w}{X_1}.\left[\frac{X_1^3\rho_w^2 g\beta\Delta T^{.}}{\mu_w^2}.\frac{C_{pw}\mu_w}{k_w}\right]^{1/3} \quad 26$$

Dunkle, (1991) also derived the following expression for h_{cw} as thus:

$$h_{cw} = 0.884\left[T_w - T_{g+}\frac{(P_w - P_g)(T_w + 273)}{0.2689 - P_w}\right]^{1/3} \quad 27$$

(c) Evaporative heat loss coefficient

The mass transfer coefficient, h_e , in terms of convective heat transfer coefficient h_{cw} , the total gas pressure, P_T, the mass of the water vapour, M_w, the air mass, M_a, the specific latent heat, L, and specific heat per unit volume at constant pressure, C_{pa} of the mixture is given by [37] as

$$\frac{h_e}{h_{cw}} = \frac{L}{C_{pa}}\left(\frac{M_w}{M_a}\right)\left(\frac{1}{P_T}\right) \quad 28$$

The expression in equation 28 is formulated owing to the assumption that;

(i) The exchange of the water vapour with the boundary layers at both the water and glass surfaces is neglected and (ii) P_w & P_g are considered small compared to P_T.

The rate of heat transfer per unit area from the water surface to the glass cover is obtained by substituting the appropriate values for the parameters in equation (28) thus;

$$\dot{q}_{ew} = 0.013h_{ew}(P_w - P_g) \quad 29$$

$$\dot{q}_{ew} = h_{ew}(T_w - T_g) \quad 30$$

From equation 29 and equation 30 we can write h_{ew} as

$$h_{ew} = 1.6273\times10^{-4}h_{cw}\left(\frac{P_w - P_g}{T_w - T_g}\right) \quad 31$$

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It is important to mention here that the value of h_{ew} can be more realistic for a larger value of $(T_w - T_g)$. The values of P_w & P_g (for the range of temperature 10°C - 90°C) can be obtained from the expression [41].

$$P_T = \exp\left[25.317 - \frac{5144}{(T-273)}\right] \quad 32$$

The total internal heat transfer coefficient h_2 is the sum of the three internal heat transfer coefficients which can be written as:

$$h_2 = \left[\frac{(T_w+273)^2 - (T_g+273)}{\left(\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_g}-1\right)}\right](T_w + T_g + 546) + 0.884\left[T_w + T_g + \frac{(P_w+P_g)+(T_{w+273})}{268.9\times 10 P_w}\right]^{1/3} + 16.273 \times 10^{-3} + 16.273 \times 10^{-3}\ h_{cw}\ \frac{P_w - P_g}{T_w - T_g}$$

33

5.0 CONCLUSION

The type of solar stills was reviewed; conventional greenhouse, V-shape glass envelope and wick. Their operations and performances were reported. The factor that affects still performances which include; climatic conditions, basin water depth, the slope of the glass cover, the thickness of the cover, the material of the cover, water glass cover temperature difference, insulation material and thickness and the surface area evaporation. And also, the energy and mass balance method of solar still conveyed and explained related to the yield of the solar still.

ACKNOWLEDGEMENT

This article is a part of institutional based research grant, fully funded by Tertiary Education Trust Fund (Tetfund) through my institution, Abubakar Tatari Ali Polytechnic, Bauchi.

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