THE EFFECCT OF INITIAL WATER DEPTH ON THE PERFORMANCE OF A SINGLE SLOPE SOLAR STILL IN YOLA, NIGERIA

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ABSTRACT

The distillation of shallow-well brackish water by the use of solar still is one of the promising methods adopted in arid zones. The population increase, economic development, in addition to global warming are creating imbalance between supply and demand of fresh water. Many developing countries faces the challenge of accessing the portable water for uses in homes and clinics despite the availability of sun shine in these regions. In this paper, a single-basin single slope solar still was design and constructed in Yola Nigeria (longitude 13°E, latitude 9.23°N) the Daily distillate was 1.49 litres at an initial water depth of 3.0 cm and 3.3 litres at an initial water depth of 0.5 cm. A maximum average efficiency of 28% was obtained. The performance evaluation for different initial water depths (0.5 cm, 1.0 cm, 1.5 cm, 2.0 cm, 2.5 cm and 3.0 cm) reveals that the daily cumulative yields are 3306 ml. 2616 ml, 2224 ml, 2006 ml, 1698 ml, 1493 ml, 1490 ml, respectively.

Key Words: Solar still, solar radiation, distill water, Cumulative yield, water depth, brackish water

1.0 INTRODUCTION

Providing adequate supply of fresh water indeed becomes the most serious problem facing the whole world at the onset of this new century. The most likely sources of fresh water are the oceans, seas and in some remote areas the wells that need to be desalinated and or distilled before it can be used. Most of the convectional distillation plants use fossil fuels or electricity as their source of energy (Van-Frassen, 2004), but in many rural locations in Nigeria, grid-connected electricity is either unavailable or, for most of the people, too expensive. Thus for such remote locations, distillation of water that employs motorised or electrical heating is not appropriate. The large initial and running cost of alternative fossil fuel powered distillers present such financial barriers that they are rarely adopted by rural people. Although a few other techniques are employed e.g. multi-effect evaporation, multistage flash distillation, thin film distillation, reverse osmosis and electrolysis, they are energy intensive and the operating cost is high as well (Van-Frassen, 2004). The direct use of solar energy using solar still is well suited for this task. The use of solar energy will become increasingly attractive with time on account of the rapid increase in price of crude oil and its possibility of extinction (Garba *et al*, 1996).

A solar still (Garg and Prakash, 1997) essentially consists of a mass of water in a container, which is covered by a transparent cover and the interior surface of this enclosure is coated black to absorb solar radiation. The cover is sloped on one side to enable the condensation to trickle into a channel. The whole enclosure is insulated to minimise heat losses from the sides and the bottom surface. Solar distillation (Mona *et al*, 2002; Bemporad, 1995; Harpreet, 1996 and Kaabi and Smakdji, 2007) represents a most attractive and simple technique among other distillation processes and is especially suited to small-scale units, environmentally friendly, simple maintenance and technology and it is appropriate to developing countries (like Nigeria) with abundant solar radiation. It is necessary therefore to search for solar stills which could provide us with the necessary daily amount of fresh water, not forgetting the drought that has been prevailing in several areas of Africa for the last two decades (Bachir, 2002).

Distilled water is required for a number of uses in both at homes and institutions for laboratory experiments, health care centres, topping car batteries etc., despite, the pressing need for drinking. In this paper the output of solar still is determined at different initial water depth to be able get the best starting depth for optimum yield

2.0 METHODOLOGY

2.1 The Study Area

Adamawa state is located in the North Eastern part of Nigeria. It lies between latitude 7 ^{0} N and 11^0 N of the equator and between longitude 11 ^{0} E and 14 ^{0} E of the Greenwich meridian. It shares boundary with Taraba State, Nigeria in the south and west, Gombe State, Nigeria in its Northwest and Borno State, Nigeria to the North. Adamawa State has an international boundary with the Cameroon republic along its eastern border. The state covers a land area of about 38741 km^2 with a population of 3,106,585 people according to the 2005 census. The state has a monthly mean sunshine hour of 220 hrs from January to April. There is a decline in this value between May and September due to increase in cloudiness over the state. The mean, during this period is 207 hours. The value increases again to 255 hours between the month of October and December. The annual sunshine (hours) ranges from 2500 hours in the south to 3000 hours in the extreme north, (Alkasum, 2006).

Figure 1: The satellite map of MAUTECH, Yola the study area

The maximum temperature in the state reaches 40 °C particularly in April while minimum temperature can be as low as 18 °C between December and January. The mean monthly temperature in the state ranges from 26.7 ^{0}C in the south to 27.8 ^{0}C in the north eastern part of the state (Dahiru *et al*, 2005). The monthly distribution of evaporation in the state generally is high due to the high insulation. The monthly distribution pattern is similar to that of sunshine and temperature which shows significant decrease during the rainy season. The seasonal variation of relative humidity shows that between January and March the relative humidity is extremely low (20 – 30) % in the state. It starts increasing as from April and reaches the peak (about 80%) in August and September. This is due to the influence of the humid maritime air mass which covers the whole state during this time. It declines again as from October following the ceasation of rains (Alkasum, 2006). Yola is the capital of Adamawa state. It is located on latitude 9.23 ^{0}N and longitude 13 ^{0}E. The altitude of Yola is 185.9 m above sea level. The majority of the residents of Yola and environs depend on water vendors popularly known as *mai ruwa (mai Moya)* for their daily water needs. These water hawkers fetch water from boreholes and shallow wells within and out side the Yola metropoli. These howked water may be liable to contamination due to many factors such as uncleanliness of the fetching environment (Alkasim *et al*., 2011).

2.2 Theoretical Background

A conventional solar still is an air tight basin made of galvanized iron sheet in a 1 m^2 base rectangular shape. The top cover is made of glass sloped at an angle approximately that of latitude of Yola and the interior surface is painted black for the maximum absorption of solar energy. Saline water is poured into the still to fill it partially and then exposed to the Sun. A typical solar still is shown in fig. (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 the moisture content of the air trapped between the water surface and the glass cover increases. The base 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 the convective heat losses. The glass cover is usually sloped to enable the water vapour which condenses on the interior surface to trickle in to a collecting trough.

2.3 The Energy Balance Equations

The energy balance for the glass cover and the water content in the basin can be expressed as follows:

$$h_1(T_w - T_g) = h_2 F_1 (T_g - T_a) \tag{1}$$

and

$$\rho_w l C_w \frac{dT}{dt} = \tau_1 H_s - h_1(T_w - T_g) - h_3 F_2 (T_w - T_b) \tag{2}$$

where ρ_w is the water density; l the water length in the basin; C_w the specific heat capacity of the water and T is the temperature, the subscripts w, g, a and b are for the water, glass, ambiant and bottom respectively; h_1, h_2 and h_3 are the heat transfer coefficients from the water surface to the glass (evaporative heat transfer coefficient), from the glass cover to the ambient (external convection heat transfer coefficient) and from the water to the basin liner (internal convection heat transfer coefficient), respectively, given by Tiwari (2002) and Garba *et al* ,(1996) as:

$$h_1 = 8.71 + h_{ew} \qquad (3)$$

where h_{ew} is the evaporative heat transfer coefficient. It is related to the pressure, P by Tiwari (2002) as

$$h_{ew} = 4.0\frac{P_w - P_g}{T_w - T_g} \qquad (4)$$

It is important to mention here that the value of h_{ew} can be more realistic for larger value of (T_w - T_g). The values of P_w and P_g (for the range of temperature 10^{o}C – 90^{o}C) can be obtained from the expression (Fernandez and Chargoy 1990).

$$P(T) = \exp\left(25.317 - \frac{5144}{T + 273}\right) \qquad (5)$$

The heat transfer coefficient, h_2 from the glass cover to the ambient is a function of wind velocity, V and is given by (Mowla and Karimi 1995) as:

$$h_2 = 5.7 + 3.8V \qquad (6)$$

The internal convective heat transfer coefficient, h_3 for heat flow from the horizontal basin (hottest region in the still) to water mass in the basin and vice-versa is determined from the following relations (Sodah *et al.*, 1980, Malik *et al* 1982 and Egarievwe 1989):

$$Nu = Co(Gr \cdot \Pr)^{n_0} \qquad (7)$$

where Nu is the Nusselt number, Gr is the Grashof number, Pr is the Prandtl number while the rest are constants given as $Nu = \frac{h_3 X_1}{k_w}$, $Gr = \frac{X_1^3 \rho_w^2 g \beta \Delta T'}{\mu_w^2}$, $\Pr = \frac{C_{pw}\mu_w}{k_w}$, respectively.

where k_w is the thermal conductivity of water in the basin; X_1 is the water-glass distance, g the acceleration due to gravity; β is the glass inclination from horizontal and $\Delta T'$ is given as

$$\Delta T' = \left[\Delta T + \frac{(P_W - P_g)(T_W + 273)}{268.9 \times 10^3 - P_W}\right] \qquad (8)$$

$$\Delta T = T_w - T_g \qquad (9)$$

For a normal operating temperature range, say 50 °C and ΔT' = 17 °C, the expression for Gr reduces to (Tiwari, 2002)

$$Gr = 2.81 \times 10^3 X_1^3 \qquad (10)$$

For the normal operating temperature range and at a spacing, $X_1 = 0.25$m; the value of the constants are:- Co = 0.075 and $n_o = 1/3$.

After substituting the values of Nu, Gr and Pr in equation (7), Dunkle, 1961 computes h_3 as

$$h_3 = 0.884\left[T_w - T_g + \frac{(P_w - P_g)(T_w + 273)}{268.9 \times 10^3 - P_w}\right]^{\frac{1}{3}} \qquad (11)$$

The energy balance for the basin liner may be written as:

$$\tau_2 H_s = h_3 F_2 (T_b - T_w) + U_{sw} F_3 (T_b - T_a) + U_{bw} (T_b - T_a) \qquad (12)$$

The factors F in equations (1), (2) and (12) are used to correct for the heat transfer areas while U_{sw} and U_{bw} are the side wall and the bottom wall overall heat transfer to the ambient.

Substituting the values of T_g and T_b from equations (1) and (12) into (2), will result into

$$M_w C_w \frac{dT_w}{dt} = aT_w + bT_a + cH_s \qquad (13)$$

where

$$a = \frac{h_3^2 F_2^2}{h_3 F_2 + U_{sw} F_3 + U_{bw}} + \frac{h_1^2}{h_1 + h_2 F_1} - h_1 - h_2 F_2 \qquad (14)$$

$$b = \frac{h_1 h_2 F_1}{h_3 + h_2 F_1} + \frac{h_3 F_2 U_{sw} F_3 + h_3 F_2 U_{bw}}{h_3 F_2 + U_{sw} F_3 + U_{bw}} \qquad (15)$$

$$c = \tau_1 + \frac{h_3 F_2 \tau_2}{h_3 F_2 + U_{sw} F_3 + U_{bw}} \qquad (16)$$

From equation (13), T_w can be calculated as a function of time. At any time the heat flux due to the evaporation can be written as:

$$Q_{ew} = h_{ew}\left(T_w - T_g\right) = \frac{h_{ew}F_1h_2}{F_1h_2 + h_1}\left(T_w - T_a\right) \tag{17}$$

The rate of water evaporation, *m* at any time is given by

$$m = \frac{Q_{ew}}{\lambda} = \frac{h_{ew}\left(T_w - T_g\right)}{\lambda} \tag{18}$$

where λ is the latent heat of vaporisation.

The total distilled water produced for a period of time *t* can be obtained by:

$$m_t = \int_0^t m dt = \int_0^t \frac{h_{ew}F_1h_2}{\lambda\left(F_1h_2 + h_1\right)}\left(T_w - T_a\right)dt \tag{19}$$

The efficiency, η of the solar still, defined as the ratio of the energy used for water production to the total solar radiation rate is given by:

$$\eta = \frac{Q_{ew}}{H_s} \tag{20}$$

As it is seen, the efficiency, η, is also a function of time.

2.4 Design and Construction of the Solar Still

The materials used for constructing the still are obtained locally from the research area. These includes: Aluminium sheet, black paint, transparent glass, headlamp gum and selotape, hard wood, ply wood and cooton wool. The features of the constructed solar still, consist of a basin (1.0 m^2 basin area) made of metal with a transparent glass cover sloped at one side at an angle of 9.23^0 to the horizontal. The basin is made up of steel and the basin liner is coated with a black paint. The whole apparatus is insulated with a 3.0 cm thick cotton wool and covered externally with plywood.

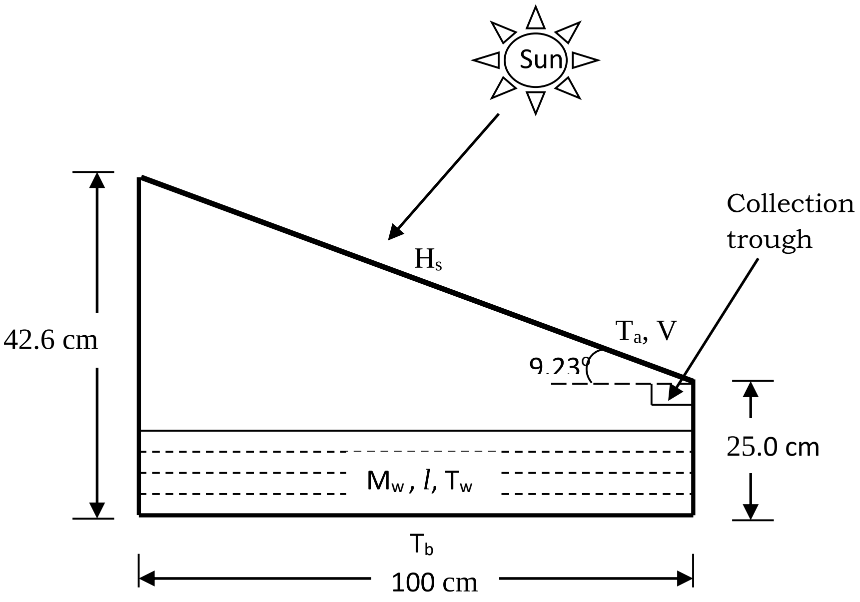

Figure 2: A side view of the constructed single-slope single-basin solar still

The still was filled with the brackish water at a shallow measured depth each morning. A slopping pane of glass, supported by an appropriate frame, covering the upper part of the basin was sealed tightly to minimise the vapour leakage. A distillate trough runs along the lower edge of the glass pane to collect the distillate and channel it out to the measuring cylinder or the rain gauge. The refilling tube for refilling the basin is located near the upper edge of the still, and a level controller which also serves as a drain to carry away the brine is located near the bottom of the still. The whole assembly is mounted on a table at the out sketch of Physics Department, MAUTECH, Yola. It is then oriented so that the slope of the still runs in east-west direction. The slopping glass cover slants towards the equator for maximum solar radiation.

The records of the monthly mean daily sunshine data for Yola, Adamawa state in the year 2010 is presented in the table 1. The set of data used in this work was obtained from the Nigerian Environmental Climatic Observing Program (NECOP) station located in the Department of Physics MAUTECH, Yola. The record was also used to comfirm the availability of sunshine in the study area necessary for the supply of the solar energy to the constructed Solar still.

3.0 RESULTS AND DISCUSSION

The measurements were done between the 20th December, 2016 and 5th January, 2017 selecting the dates with similar atmospheric condition. The minimum monthly average daily sunshine hours was 6.13 and the maximum was 8.77 hrs (Table1). This implies that the condition is favourable for effective usage of a solar still throughout the year.

Table 1: Average Climatic Conditions of Yola (Latitude 9.23 °N; Longitude 13 °E) for the year 2017

Month	Solar radiation, H_S (Wm^{-2})	Ambient temp., T_a (°C)	Relative humidity, RH (%)	wind speed, V (ms^{-1})	Sun-shine (Hrs)	Monthly mean daily sun shine (Hrs)
Jan	215.2	27.2	18.9	0.763	234	**7.80**
Feb	202.9	25.8	18.6	0.774	217	**7.23**
March	200.2	31.3	23.8	0.660	205	**6.83**
April	238.6	33.6	15.8	0.900	224	**7.47**
May	207.7	33.5	29.1	0.873	238	**7.93**
June	197.1	30.5	56.3	0.991	222	**7.40**
July	186.6	28.8	64.0	0.976	184	**6.13**
Aug	177.3	27.3	69.7	0.882	187	**6.23**
Sept	162.9	26.3	75.5	0.738	202	**6.73**
Oct	186.3	27.9	79.0	0.615	248	**8.27**
Nov	210.8	28.1	79.8	0.569	263	**8.77**
Dec	221.1	28.0	80.2	0.509	255	8.50

Source: NECOP Data Station, Department of Physics MAUTECH, Yola (2016)

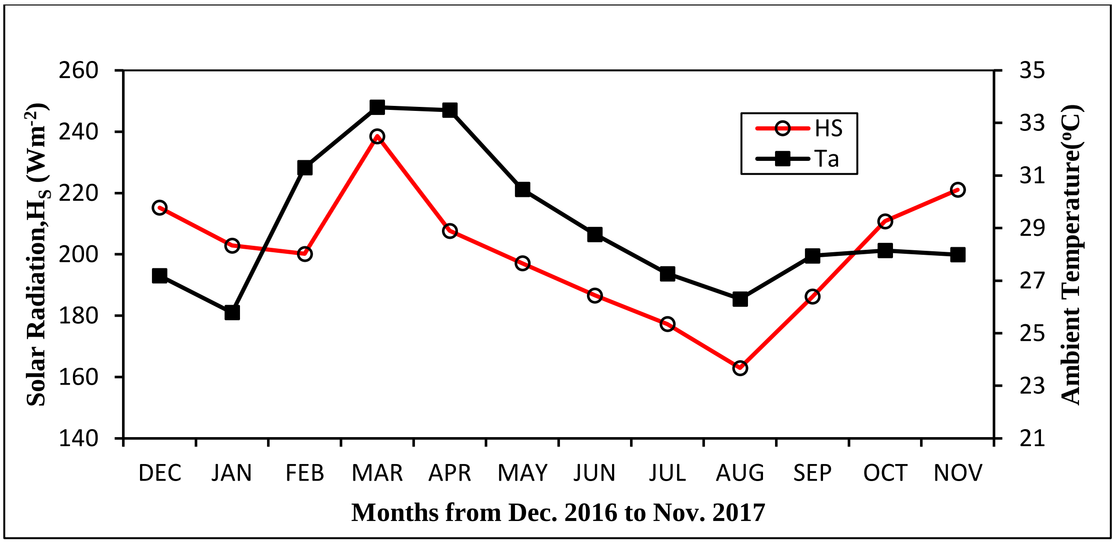

Figure 3: The variation of Monthly average solar radiation, H_s and ambient temperature, T_a over a year (December 2016 to November 2017) in Yola.

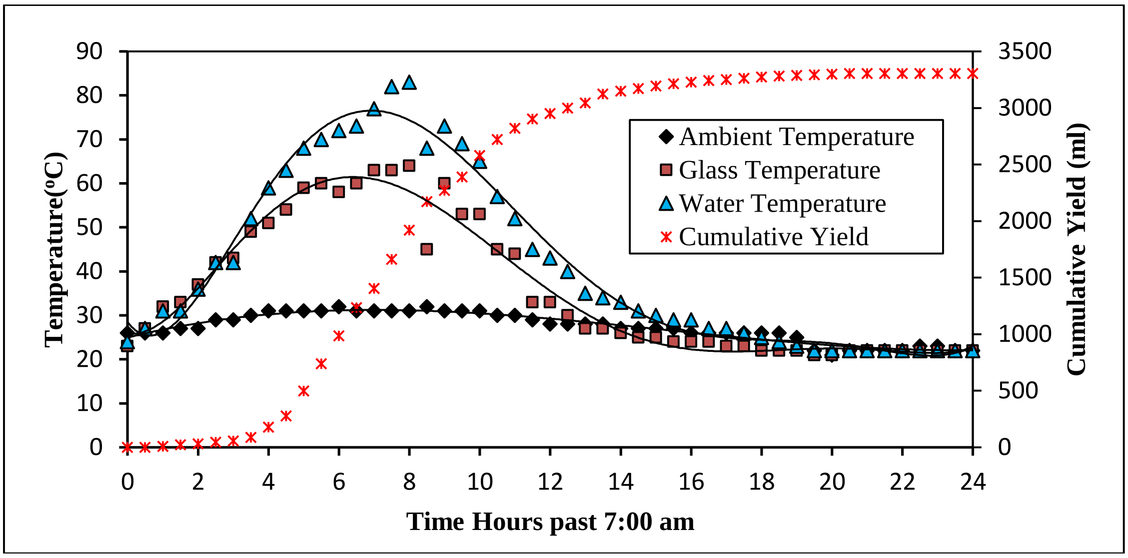

Figure 4: The variation of the Distiller Cumulative Yield and Distiller variables with time at an initial water depth of 0.5 cm Date 30th December, 2016. The marked points indicated the experimental data points while the solid line gives the fit for the polynomial regression of the plots.

At an initial water depth, the variation of the still charateristics (Ambient, Glass, and water) temperatures as well as the cumulative yield with day times were as presented in figure (4). At arroud 2:00 PM which is the 8th hour past 7:00 AM the three temperatures clearly distinguish themselves with substainitial difference, enabling the evaporation of the brackish water hence the distillate production which was cumulatively adds up. the yeild was high between the 6th and 10th hours.

The cumulative yields for the different initial water depths considered were presented in figure (5). frobm the figure it indicates that at 0.5 cm initial warter depth tha yield was highest (3.3 L) and it was the least at initial depth of 3.0 cm with the yiel of 0.49 L. the variation of the yield with an initial depths was presented in figure 6, which indicates that the yield reduces with the increase in the initial water depth. thereby suggesting that for optimum results apart from the favourable whether comnditions, a very shallow water depth is requred.

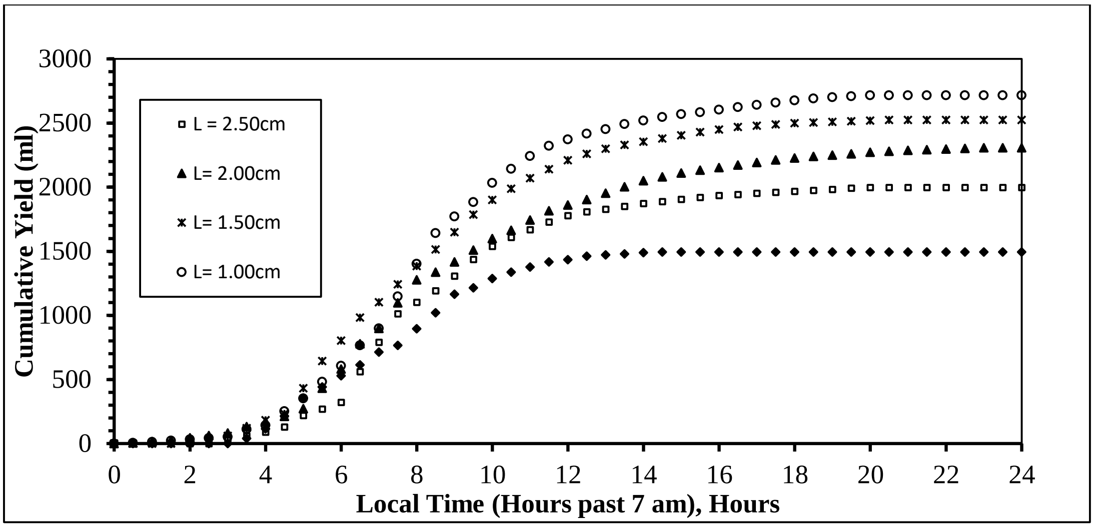

Figure 5: The Cumulative yield at different initial water depths. The marked points indicates the experimental data points obtained for the various initial water depth.

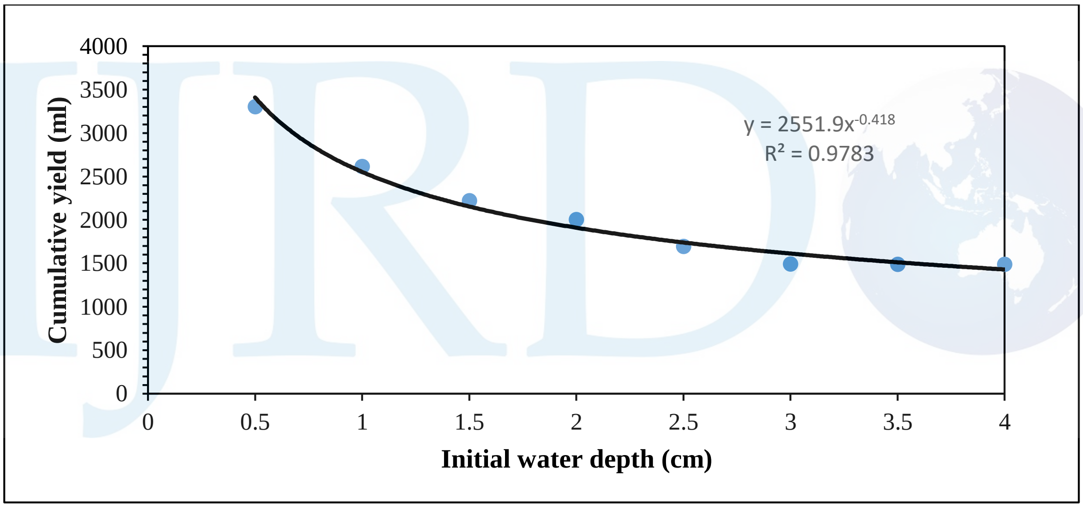

Figure 6: The variation of the Daily yield with the initial water depths. The marked points indicates the experimental data points for the various initial water depth while the solid line indicates the power average tredline with R^2 value of 0.98.

4.0 CONCLUSION

The literature has it that the cumulative yield of a solar distiller unit depends on the initial water level (Tiwari 2004). From the results obtained, figure 4 presents the variations of the yield with time at various initial water depths. The figure shows that as the initial water depth decreases the cumulative yield increases from initial depth of 0.5 cm to 3.0 cm at steps increments of 0.5 cm. This implies that at the initial water depth higher than 3.0 cm many of the evaporated water molecules drop back into the basin water due to high thermal energy and shorter water – glass distance which are the prime factors of the still performance.

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