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Design of a Solar Distillation Still Model with Backup Heat from Biomass

Olawale James Okegbile[1], Sunday Bako[2*], Folorunso Olayiwola Akinbode[3], Vincent Obiajulu Ogwuagwu[4], James Oseni Abu[5]

[1,3,4,5]Department of Mechanical Engineering, Federal University of Technology Minna, Nigeria.
[2]Department of Mechanical Engineering, Nuhu Bamalli Polytechnic, Zaria, Nigeria.*

Corresponding Email: [2]s2bako@yahoo.com*

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***Abstract:** Water borne pathogens caused series of diseases, and millions died each year. Therefore, availability of safe drinking water and good water sanitation is of great global importance, while this can be done through solar still distillation. The distillation process is one of the technologies for water processing and purification, and solar energy is the main source of energy that used to energize the process. Therefore, in this paper, a solar distillation still with back-up heat from Biomass has been designed with basin area of 1.045 m^2 (1290 mm x 810 mm). However, various design equation were utilized during the design process. The energy requirement for evaporating water is 226 0kJ/kg. This implies that much heat energy is required to produce 1 litre of pure. For this reason, a collector of 1.044m^2 area was used. This will provide sufficient energy for distillation process. The solution obtained from the Polymath 5.0 software, shows that, the day is not as intrinsic as the solution for the night. This might be due to supply of heat as concentrated heat unlike for the day when the heating increased relatively gently. It is hereby recommended that more of the machine should be develop and made available in the market to enhance a safer and more sanitize drinking water for the society.*

***Keywords:** Solar Still, Distillation Still Model and Design.*

1. INTRODUCTION

Water distillation using solar energy, is a renewable energy technology with a very long history and were used for salt production rather than drinking water [1]. A simple solar still distillation model consist of a water basin and a single glass cover. In a conventional solar still, the heat of vapourization received by the glass cover gets lost to the surrounding mainly by convection and radiation. A simple schematic diagram of a tilted Solar-Still distillation

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model is shown in Figure 1 below.

Water in many rural areas infects users with many water-borne diseases which can results in ill-health and sometimes death. To address these problems, there is need to use a large distillation model to produce large quantity of accessible water for human consumption [2-4]. Solar distillation provides a cheap method for water purification. However, production rate of Solar still is low and thermal inertia in the early hours of the day is responsible. Therefore, this paper tends to address this problem by designing a solar distillation system with backup heat from biomass which can be used in both rural and urban areas.

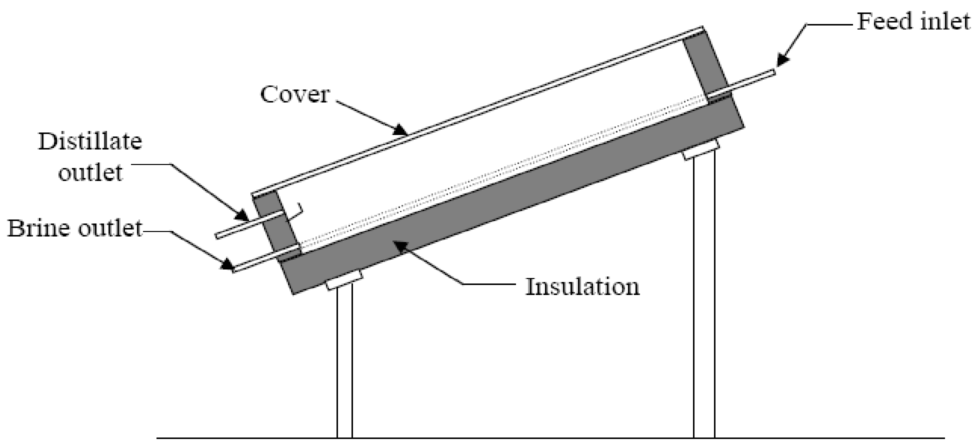

Figure 1: A Schematic of a Tilted Solar Still Distillation Model

Over 97% of water on the earth surface is salty; the remaining 2.6% is fresh water, while less than 1% of the fresh water is available for human consumption. The permissible limit of salinity in water is 1500 ppm while most of the water available on earth has salinity as high as 5000ppm. The arid and semi-arid countries, with about 40% of the world's population experience intense periodic droughts [5-6]. Desalination has become in many parts of the world, a reliable source of fresh water for human consumption. The different methods used in desalination are based on thermal or membrane principles. Among the modern thermal methods used for desalination is solar distillation. Interest in solar distillation rises from the fact that areas of fresh water shortages have much solar energy. It's low operating and maintenance costs make it an attractive method in remote areas where there is no electricity supply.

2. RELATED WORKS

Researchers [7-11], presented methods and strategies to modify the design and operation of a solar water distillation model. Katekar and Deshmukh [7] conducted a techno-economic analysis of different types of solar distillation models to enhance its efficiency. Prakash and Velmurugan [8], Sivakumar and Ganapathy [9] and Tuly et al. [10] highlighted methods and strategies to improve the effectiveness of solar still distillation models. While, Patel and Modi

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[11], shows the different approached used to improve the performance of solar stills with improvement in condensation.

Naim et al. [12] uses charcoal particles to increase production of distil water by 15% with a wick-type stills. Nafey et al.[13] carry out experiment using a black rubber and black gravels with a single-tilted solar still as a storage. It was noted that the black gravel absorbs and discharges the incident solar energy faster rate than the black rubber. Iy was also noted that the black gravel of 20–30 mm increased the efficiency by 19% with 20 litres of salty water and with titled angle of 15°. Badran [14] obtained 29% increase in productivity with sprinkler combination with asphalt. Nijmeh et al., [15] noted that the effectiveness of solar still can be influence by 26% when using potassium dichromate with water as an absorbing material. While Bilal et al., [16] stated that solar still can be improve with some rubber material. It was noted that the rubber material enhanced the daily water production capacity by 38%. Kumar and Tiwari [17] concluded that an active solar still having water flowing over the glass cover, will gives a high productivity than a still alone. Voropoulos *et al*. [18] studied the characterics of a solar still coupled with a hot water storage tank. It was noted that this system gives to a higher output of distilled water. Therefore, this paper aimed to design a solar distillation still with back-up heat using biomass for the purpose of improving the daily distillate yield of solar still using waste organic materials.

Solar Still

2.1 Distillation Still Models

A model was proposed by Zurigat and Abu-Arabi, [19] to predict the distillation still productivity. While, an input-output method was applied by Mathioulakis *et al*. [20] in which the concept was to develop energy balance based on the following premises:

1. The characteristic reference was deployed by changing of solar variables and it coincides with the daily cycle.
2. The solar energy of the outflows was equal to the inflows by subtracting the environmental losses.
3. The environmental losses can be considered as the temperatures difference between the inside and outside of the system.
4. The distilled water produced daily indicates the system outflows

The above premises (serial No. 1-4) led to the basic input-output equation given as Equation 1.

$$m_w = f_1 H + f_2(\bar{T}_w - \bar{T}_a) + f_3 \tag{1}$$

This equation derived from instantaneous thermal balance of the solar still by considering the equation that gives the mass rate of the produced water, (Equation 2 and 3).

$$\frac{C_w}{\beta_w \frac{dT_w}{dt}} = k(t)\eta_o I(t) - U_t[T_w(t) - T_a(t)] - U_b[T_w(t) - T_a(t)] \tag{2}$$

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$$\overset{*}{m} = \frac{h_{ewg}\beta_g}{h_{fg}}\frac{U_t}{U_i}[T_w(t) - T_a(t)] \tag{3}$$

From Equation 26, the daily input-output equation for the day is given by Equation 4.

$$m_{w,d} = f_{1d}H_d + f_{2d}(\overline{T}_{w,d} - \overline{T}_{a,d}) + f_{3d} \tag{4}$$

Considering the fact that there is no solar energy at night, the input-output equation for the night is given by Equation 5.

$$m_{w,n} = f_{2n}(\overline{T}_{w,n} - \overline{T}_{a,n}) + f_{3n} \tag{5}$$

The problem of knowledge of average water temperature was envisaged and the author derived equations for daily and nightly water temperatures. Taking into account that the input consists of solar gain and output the heat losses by evaporation and through the walls is valid equation 6.

$$T_{w,k} = \sum_{i=k-n}^{k}\left[j_{1,i}H_i + j_2(\overline{T}_{w,i} - \overline{T}_{a,i}) + j_{3,i}m_w\right] \tag{6}$$

The first term represents the solar gain, the second the environmental losses, while the third the losses by water's evaporation. The thermal memory of the still is limited to 2 days, therefore that leades to Equation 7 and 8,

$$\overline{T}_{w,d} = f_1H_d + f_2\overline{T}_{a,d} + f_3\overline{T}_{a,n} + f_4H_{d-1} + f_5\overline{T}_{a,d-1} \tag{7}$$

$$\overline{T}_{w,n} = l_1\overline{T}_{a,n} + l_2H_d + l_3\overline{T}_{a,d} + l_4\overline{T}_{a,n-1} \tag{8}$$

The combination of Equations 6 and 8 led to formation of Equation 9 and 10.

$$m_{w,d} = a_1H_d + a_2H_{d-1} + a_3\overline{T}_{a,d} + a_4\overline{T}_{a,n-1} + a_5\overline{T}_{a,d-1} + a_6 \tag{9}$$

$$m_{w,n} = b_1\overline{T}_{a,n} + b_2H_d + b_3\overline{T}_{a,d} + b_4\overline{T}_{a,n-1} + b_5 \tag{10}$$

The determination of the coefficients a_1 …..a_6 and b_1 ….b_5 can be carry out using the coefficients of Equations 6 to 8 or directly using multidimensional least square regression method. Some authors used 82 days data for fitting. The percentage error was about 0.01% which implies non-systemic errors. The daily Positive and negative deviations were compensated over a long period. The possibility of using this model for the combination of day and night however gave unsatisfactory result of typical errors. The standard error is given by (Equation 11),

$$S_x = \sqrt{\sum_N \frac{(x_{model} - x_{exp})^2}{N}} \tag{11}$$

Voropoulos *et al.* [14] considered the input-output model with another approach. The operation of a solar still is characterized by three phases. The second phase is the most

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important stage, during which the distillation occurs to produce the daily distilled water. During this phase, the cumulative water production curve has been observed to be linear, indicating that the output can be correlated with existing climatic conditions in a daily base by deploying Equation 12.

$$M_{out,d} = f_{1d} H_d + f_{2d} (T_{wd,in} - T_{a,d}) + f_{3d} \tag{12}$$

This equation combined the output of the daily water production $M_{out,d}$ with the input of the incident solar energy H_d and the level at the starting of the operation, represented by the temperature difference between the temperature of the saline water at the beginning of the day $T_{wd,in}$ and ambient temperature of the air $T_{a,d}$ and using f_{1d}, f_{2d} and f_{3d} coefficients (Equation 13-18).

$$f_{1d} = \frac{F_1 + \dfrac{F_2 A_w \eta_{od} \bar{k} F}{2FC_w}}{1 + \dfrac{F_2 (U_t + U_b) A_w}{2FC_w}} \tag{13}$$

$$f_{2d} = \frac{F_2}{1 + \dfrac{F_2 (U_t + U_b) A_w}{2FC_w}} \tag{14}$$

$$f_{3d} = f_{1d} H_{1ph} \tag{15}$$

Where,

$$F_1 = \bar{k}_d \, \eta_{od} \frac{A_g A_w}{C_w} \frac{h_{ewg}}{h_{fg}} \frac{U_t}{U_i} (\Delta t)^2 \tag{16}$$

$$F_2 = (U_t + U_b) \frac{A_g A_w}{C_w} \frac{h_{ewg}}{h_{fg}} \frac{U_t}{U_i} (\Delta t)^2 \tag{17}$$

$$F = A_g \frac{h_{ewg}}{h_{fg}} \frac{U_t}{U_i} \tag{18}$$

The water basin temperature at the end of the day is given Equation 19.

$$T_{w,d} = A_w \eta_{od} \bar{k} F H_d - \frac{(U_t + U_b) M_{out,d} A_w}{FC_w} + T_{1,d} \tag{19}$$

For the night operation, the 'input-output' expression is similar to Equation 16 but not having the radiation term

$$M_{out,n} = f_{2n} (T_{wn,in} - T_{a,n}) + f_{3n} \tag{20}$$

$$f_{2n} = \frac{F_{2n}}{1 + \dfrac{F_{2n} (U_t + U_b) A_w}{2FC_w}} \tag{21}$$

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$$F_2 = (U_t + U_b)\frac{A_g A_w}{C_w}\frac{h_{ewg}}{h_{fg}}\frac{U_t}{U_i}(\Delta t_n)^2 \quad (22)$$

In this case, the coefficient f_{3n} does not exist. The water basin temperature at the end of the night given by Equation 23.

$$T_{w,n} = \frac{(U_t + U_b)M_{out,n}A_w}{FC_w} + T_{1,n} \quad (23)$$

Some authors used least-squares regression method for real water output $M_{out,d}$ using the total solar radiation H_d and temperature difference ($T_{wd,in} - T_{a,d}$) for the entire experiment to determine the values of characteristic coefficients f_{1d}, f_{2d}, and f_{3d} for the day. Their result is as shown in Table 1.

Table 1: Determination of Characteristic Coefficients for the Day Operation and Comparison with Real and Predicted Water Output [14]

S/N	Parameter	f_{1d}	f_{2d}	f_{3d}	Difference (kg)	σ_1 (kg)
1	Coefficient	1.24	1.13	-11.01	≈ 0	3.43
2	Deviation	±0.09	±0.26	±1.67		

3. MATERIALS AND METHODS

3.1 Design Concept
Design is the process of translating an idea or a need into detailed information from which a product is to be made. Often, the choice of material is dictated by the design. A material being designed should satisfy various requirements outlined in the specification [21].

3.2 Design Considerations
One of the major costs involved in solar heating systems is that of the collector, which depends upon designing the least expensive practical collector; the most important considerations in collector design are the efficiency and cost effectiveness. For the best results of this design, the following has to be taken into consideration.

1. The quantity and type of material for the cover used with special emphasis on its transmissivity and cost
2. The cover tilt angle should be for optimum performance of the collector
3. The insulation material should have low thermal conductivity and be adequate to reduce both side and bottom losses. Also, the least costly available material will be preferred.
4. The absorber material should have high thermal conductivity.

3.3 Location Information
Minna on the geographical map is located as follows [22],

Altitude of Minna	323 m
Latitude of Minna	$9°37^{11}$
Longitude of Minna	$6°33^{11}$

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3.4 Material Selection

The material chosen for the transparent cover was selected based of the following properties:

1. It should have a high coefficient of transmissivity
2. It should be stable at high working temperatures
3. It must be unaffected by ultraviolet radiation
4. It should have low density

Glass was selected as the transparent cover material because of its high transmissivity and stability at high temperature, and the sheet metal was selected for the construction of absorber plate because it has fair corrosion resistance when painted, cheap and always available. The insulating material was selected based on the following properties,

1. It must be of low thermal conductivity
2. It should have low density
3. It should be available

The material for combustion chamber were selected based on the following properties,

1. High ability to withstand heat and fire
2. Strong enough to carry the weight of underlining bricks.
3. It should be available and cheap

3.5 Development of Model Equations

Model for the Day Water Production

Mathiolakis *et al*. [20] worked on input-output model using equation (22) involving total daily solar radiation, H, mean water daily temperature and ambient temperature. This model expresses the mass of distillate as dependent on daily mean solar radiation for the day, and the difference between mean daily water basin temperatures.

3.5.1Model for Night Water Production

The model being proposed for water produced at night due to combustion of biomass follows similar premises as in the case of the day when solar energy alone was considered expect that at night when there is no solar radiation, biomass is being burnt to replace heat derived from the sun. Replacing the solar gain term with quantity of heat derived from burning m_b mass of biomass, Equation (24) was obtained.

$$m_{w,n} = f_{1n} m_b Q_b + f_{2n} (\bar{T}_{w,n} - \bar{T}_{a,n}) + f_{3n} \qquad (24)$$

Where,

$\bar{T}$ = Mean daily temperatures, f = coefficients of equation

m_b = mass of biomass burnt Q_b = Calorific value of biomass used

The first term expresses the gain due to the combustion of mass, m_b of biomass; the second part expressed the environmental losses, while the third term expressed the losses by evaporation.

3.5.2 Model for all Day Water Production for Solar and Biomass

The model being proposed for all day round (hybrid) follows similar premises as in the case

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of the day when solar energy alone was considered. The sun heats in the day while biomass heats at night. The equation governing the hybrid therefore combines the two heat sources.

The resulting to Equation (25)

$$m_w = f_1 \overline{H} + f_2 m_b Q_b + f_3 (\overline{T}_w - \overline{T}_a) + f_4 \qquad (25)$$

The first and second terms express the solar gain in the day and heat gain from combustion of biomass at night respectively, the third term is the environmental losses and the fourth term is the losses by water's evaporation.

3.5.3 Design Features

There are many designs of solar still models by different researchers and manufacturers. This can be categorized into passive and active (Malik *et al*, 1982; Al-Hayek and Badran, 2004; Kalogirou, 1997; Singh and Tiwari, 1993; Kumar and Tiwari, 1996; Naim and Abd El Kawi, 2002). The effect of different designs of solar stills on yield was investigated by Al-Hayek and Badran (2004). It was noted that the productivity of an asymmetric greenhouse still with mirrors at inside walls was 20% more than that of the symmetric type.

The solar still with back-up heater consists of a stand, evaporation chamber, glass cover, collecting trough, distillate container, and combustion chamber. The parameters determined include dimensions to be used for construction of the distillation still, the volume of the components, volume and mass of material for the construction of the individual components and total surface area of the components. The isometric view of the design presented in Figure 2 and 3 respectively.

3.5.4 Evaporation Chamber

The evaporation chamber served as the solar energy collector in this work. The inner walls and the outer walls are to be made of sheet metal gauge 22 which is to be painted black in order to influence the absorption of solar radiation. The outer wall is also to be made of sheet metal because of resistance to fire since back-up heat will be provided from combustion of biomass materials. The absorber plate is of gauge 22 since it will be fired directly from the bottom. It is also to be painted black for maximum absorptivity since it will also absorbs solar radiation to operate in the day.

In solar distillation research, still performance is measured per square meter of evaporation chamber per day [8, 10, 23, 24, 25], therefore, 1m2 area of basin was used to provide a straight base for possible comparison with previous works. Absorption of solar energy is also influenced by aspect ratio (the ratio between length and width of the still). El-Swify and Metias [26] noted that the solar radiation reflected from the walls of a still is optimum if the length is twice its width. However, non-optimum values have been used in some of the previous researches, based on the objective of the research. Aspect ratio of 1.6 has been decided since it is within acceptable range.
The transparent cover has an area (A_g) of 1.044m^2 (0.81m x 1.29m), and the mass of the glass used as the transparent cover for the still is given by equation 26.

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$$M_g = \rho_g A_g d_g \tag{26}$$

Mass of sheet metal used for the evaporator is given by equation 27,

$$M_{ev} = \rho_s A_s d_s \tag{27}$$

3.5.5 Collecting Trough

The collecting trough is needed to collect the distillate coming from the sloping glass cover. This trough is to be produce from aluminium roofing sheet, but it is usually preferable to construct it from material that is a bad conductor of heat so as to prevent re-evaporation of the condensate from the trough. The major reason why aluminium is chosen is because of the expected quality and purity of water collected. Aluminium is relatively safe to carry distilled water. The trough is in the form of a semi circular shape sloped by about 3 degree for easy flow of distillate (Equation 49).

$$A_{tv} = \frac{\pi d^2}{8} \times L \tag{49}$$

$$M_t = \rho_{al} A_t d_t \tag{48}$$

3.5.6 The Stand

The stand is to be made from 0.051m x 0.051m (2 x 2 inches) angle iron and is constructed in such a way that it wound round to the top of evaporator for the entire still to stand very rigid.

3.5.7 Combustion Chamber

The combustion chamber is to be underlined round the walls and the bottom with fired clay bricks of 0.02 meter thickness for insulation to minimize heat leakage through the walls and bottom. Chimney is also be used for the exhaust of the products of combustion with 0.09m diameter iron pipe of length 1.06 m.

3.5.8 Insulation of the Walls of Evaporation Chamber

Fibre glass material is to be used for the insulation of the walls of the evaporation chamber round the sides. The bottom is not be insulated since it is exposed to the combustion chamber for the burning of biomass.

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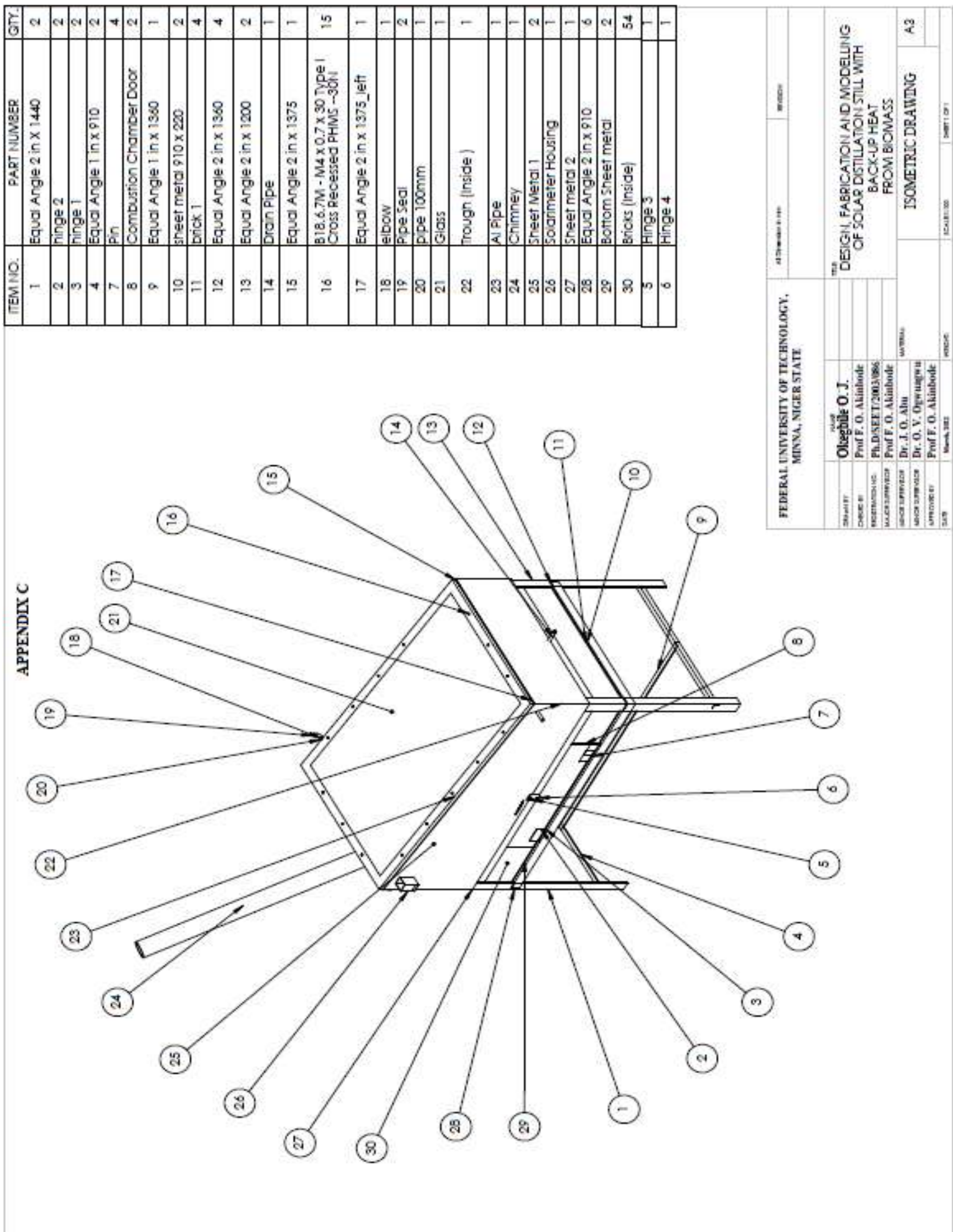

Figure 2: The Machine Drawing

4. RESULTS AND DISCUSSION

Alternative heat supplied at night will yield increased distillate. In the rural areas especially of the developing countries, dead plants and waste organic matters exist that can serve as source of cheap heat. These waste sources when used to supply heat to augment solar still will produce more distilled water and leave the environment cleaner. Most of these biomass are being burnt anyway hence there is no addition to the greenhouse gases released as a result of burning them to augment the solar still.
It was noted that the performance of conventional solar distillation models has beem

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predicted by different methods such as Computer Simulation [27-28], thermic circuit and the Sankey – diagrams [28], periodic and transient analysis [29-33], iteration methods [34], numerical methods [35-36]. However, Bori *et al.*,]37] design a solar heater with the solar collector area of 0,76m^2; this produces the outlet temperature of 65^{o}C during the raining season, and the temperature of 79.3^{o}C during the dry season. Comparing the size of this collector and the one used in this present work (1.0454m^2), is can be stated that, this present design can generate the temperature of 89.4^{o}C during the raining season, and the temperature of of 109.1^{o}C during the dry season. Therefore, this design will effective, however, the performance this solar distillation predicted using Polymaths 5.0 software.

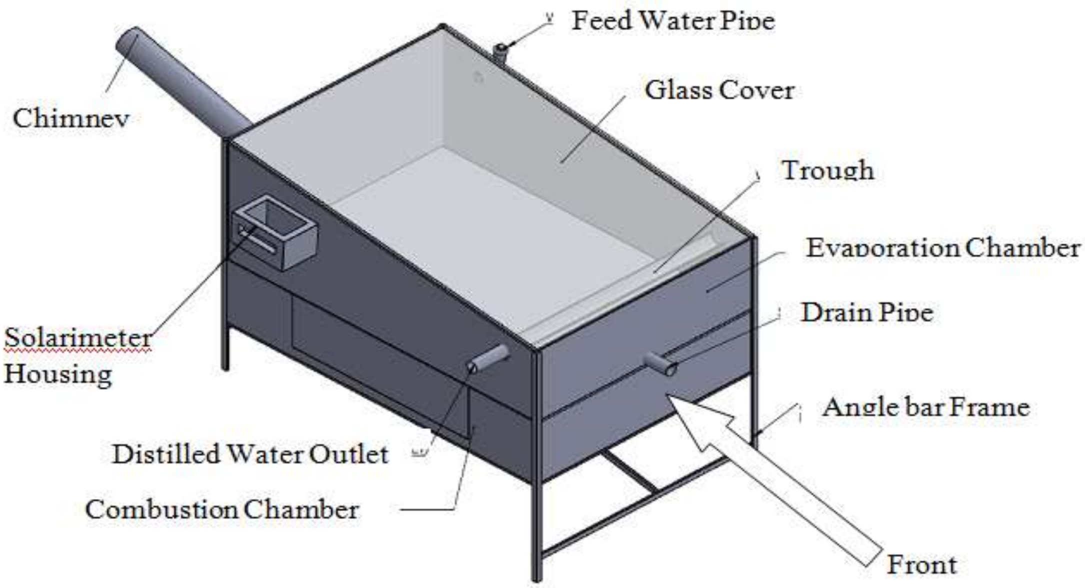

Figure 3: Perspective View of the Distillation Still

4.1 Model Equations

Sub-section 5.1.1-5.1.3 below show the solutions to the model equations. Solution obtained for the day is not as intrinsic as the solution for the night. This might be due to supply of heat as concentrated heat unlike for the day when the heating increased relatively gently.

4.1.1 Results of Model Solution from Polymath 5.0 Software for Solar Energy Alone

LEQ Solution

[1] x_1 = -0.0057057
[2] x_2 = 0.0689489
[3] x_3 = 1.5900601

LEQ Report

Coefficients matrix and beta matrix

x_1	x_2	x_3	
270.4	16.4	1	| 1.178

279.8	17.7	1	| 1.214
267.9	15.7	1	| 1.144

The equations
[1] $270.4 \cdot x_1 + 16.4 \cdot x_2 + x_3 = 1.178$
[2] $279.8 \cdot x_1 + 17.7 \cdot x_2 + x_3 = 1.214$
[3] $267.9 \cdot x_1 + 15.7 \cdot x_2 + x_3 = 1.144$

General
Number of Equation: 3

4.1.2 Results of Model Solution from Polymath 5.0 Software for Night Only

LEQ Solution
[1] $x_1 = 0.0208867$
[2] $x_2 = -0.0553333$
[3] $x_3 = 1.6948$

LEQ Report
Coefficients matrix and beta matrix

x_1	x_2	x_3	
180	26.7	1	| 3.977
150	21.9	1	| 3.616
120	20.1	1	| 3.089

The equations
[1] $180 \cdot x_1 + 26.7 \cdot x_2 + x_3 = 3.977$
[2] $150 \cdot x_1 + 21.9 \cdot x_2 + x_3 = 3.616$
[3] $120 \cdot x_1 + 20.1 \cdot x_2 + x_3 = 3.089$

General
Number of Equations: 3

4.1.3 Results of Model Solution from Polymath 5.0 Software for Night and Day (Hybrid)

LEQ Solution
[1] $x_1 = 4.815E+12$
[2] $x_2 = 0.0164469$
[3] $x_3 = -0.0245593$
[4] $x_4 = -7.055E+14$

LEQ Report
Coefficients matrix and beta matrix

x_1 x_2 x_3 x_4

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146.5	180	23.3	1	| 5.109
146.5	150	20.8	1	| 4.714
146.5	120	19.8	1	| 4.243
146.5	90	19.1	1	| 3.744

The equations
[1] $146.5 \cdot x_1 + 180 \cdot x_2 + 23.3 \cdot x_3 + x_4 = 5.109$
[2] $146.5 \cdot x_1 + 150 \cdot x_2 + 20.8 \cdot x_3 + x_4 = 4.714$
[3] $146.5 \cdot x_1 + 120 \cdot x_2 + 19.8 \cdot x_3 + x_4 = 4.243$
[4] $146.5 \cdot x_1 + 90 \cdot x_2 + 19.1 \cdot x_3 + x_4 = 3.744$

General
Number of Equations: 4

5. CONCLUSIONS

Access to safe water cannot be over emphasized. In developing countries where there is no portable water, boiling of water is mostly used for sanitizing water human consumption. Distillation guarantees pure and fresh water devoid of any dissolved salt or other contaminants. Apart from drinking, distil water is useful in areas such as hospital, battery, pharmaceuticals.
In this research, effort was geared towards making use of heat from waste biomass to augment available heat from the Sun. This will stabilizes water production and eliminates initial thermal inertia and increases daily production as there is more distillate overnight when the ambient temperature is lower than in the day. There is no doubt that, a high efficiency will obtain after construction and testing of this solar distillation still with back-up heat from biomass. This is due to the series of design consideration taken into account during the design process. It is hereby recommended that more of the machine should be produce to enhance a safer and more sanitize drinking water for human consumption.

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