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Full Length Research Paper

Theoretical analysis of water distillation using solar still

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In developing countries, lack of safe and unreliable drinking water constitutes a major problem. To alleviate this problem, a solar still was designed and tested in Mubi, Adamawa State of Nigeria. The radiation from the sun evaporates water inside the solar still at a temperature higher than the ambient. The principle of operation is the greenhouse effect provided with the glass cover. Energy balances are made for each element of the still; solar time, direction of beam of radiation, clear sky radiation, optical properties of the cover, convection outside the still, convection and evaporation inside are accounted. Theoretical analysis of the heat and mass transfer mechanisms inside this solar still has been developed. The measured performance was then compared with results obtained by theoretical analysis. The results clearly show that the instantaneous efficiency increases with the increase of solar radiation and with the increase of feed water temperature. The distillation efficiency of the still is 99.64% as compared to the theoretical analysis.

Key words: Solar still, greenhouse effect, ambient, convection, evaporation, feed water.

INTRODUCTION

Portable water may be described as water fit for human consumption (Medugu and Malgwi, 2006). Supply of portable water is a major problem in underdeveloped as well as in some developing countries. Along with food and air, water is a basic necessity for human beings. However, a large fraction of the World's population, about 1.1 billion people, do not have access to improved or microbiologically save source of water for drinking and other essential purposes (WHO, 2002). In addition, there are many coastal locations where sea water is abundant but portable water is not available. It is really very fortunate that in terms of high water demand, solar radiation is also intense. It is therefore beneficial to exploit solar energy directly by installing solar stills. Two major advantages favor the use of solar stills – clean and free energy and friendly to environment.

The consumption of save or quality water based on its source, extent of treatment or consumer handling do not take into consideration several well – documented problems. One of the problems is protected or improved sources, such as boreholes and treated urban supplies, can still be contaminated such that microbiologically unsafe water is delivered. In some cities in Nigeria, the water systems draw unsafe water from unprotected or contaminated sources and deliver it to consumers with no or inadequate treatment. Yet, these water systems are classified or categorized as improve or safe. Another problem is contamination of water during distribution; whether water is piped or carried into the home. Many communities have protected improved water supplies and treated water that is microbiologically safe when collected, or when it leaves a treatment plant. However, substandard water distribution systems, intermittent water pressure due to power outages and other disruption and illegal connections to the distribution system often lead to the introduction of fecal contamination and therefore, microbiologically contaminated water at the consumer's tap or collection point (Sobsey, 2002).

A further problem is that water collected for domestic use often becomes re – contaminated or further contaminated by unsafe consumer storage and handling practices at the household level. Many people continue to obtain their water on daily or frequent basis from any available source and either carried it or otherwise have it delivered to the home for personal use. Typically, this water is not treated or otherwise protected from subse-

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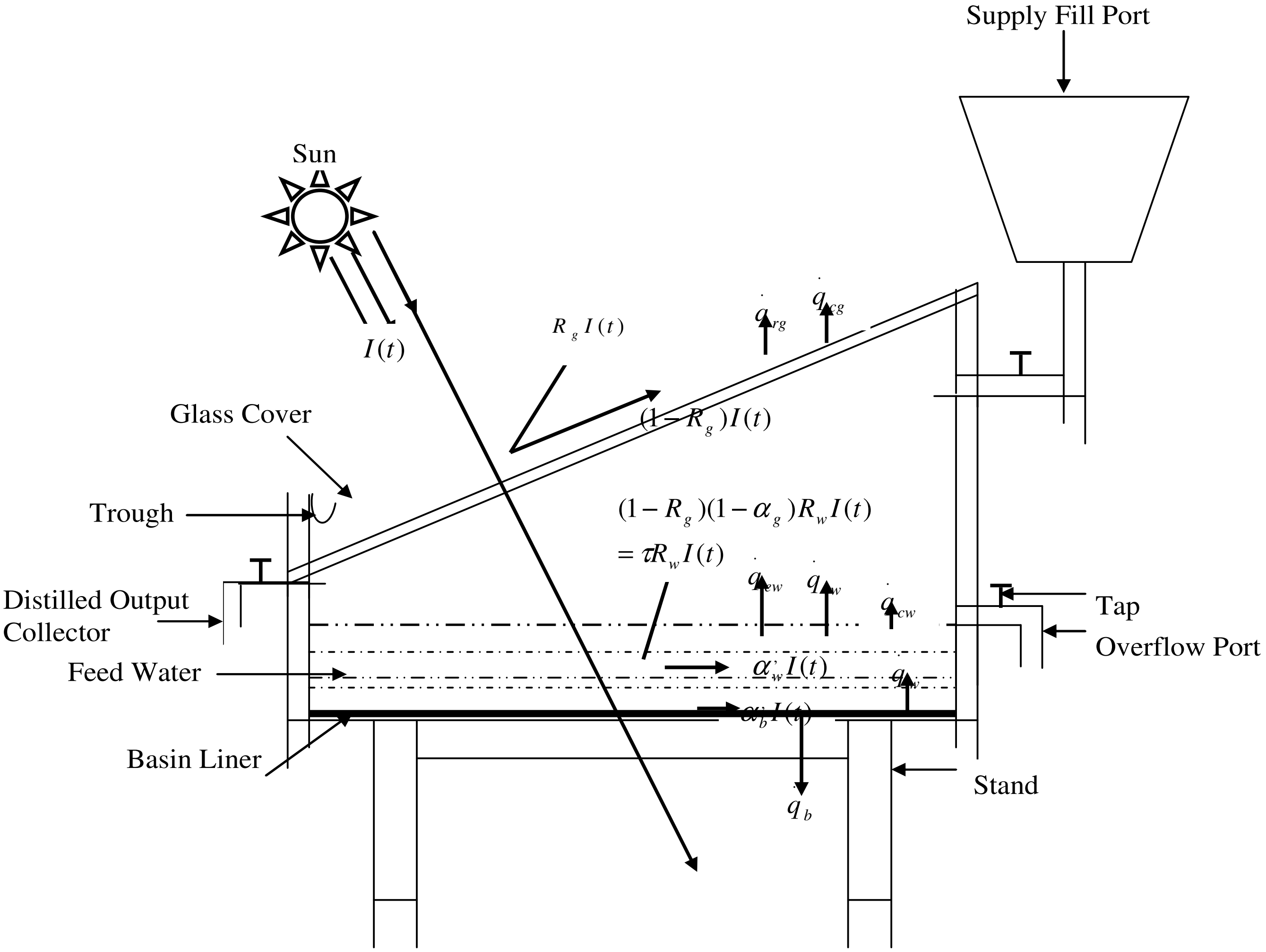

Figure 1. Schematic of the system.

quent contamination during use. Such household water is at the risk of being contaminated by various pathogenic viruses, bacteria and parasites associated with feacal wastes and other sources (Sanyaolu et al., 2002).

Distillation is a good method to obtain portable water. However, the conventional distillation processes such as multi – effect fresh evaporation, thin film distillation, reverse osmosis and electrodialysis are energy intensive techniques and are not feasible for large fresh water demands. Therefore, solar distillation seems to be a promising method and an alternative way for supplying small communities in remote areas and islands with water. In fact, it has been reported that for such places, solar distillation could be the most favorable way for water supply. Indeed, several solar still designs have been proposed and many of them have found significant application worldwide. Nevertheless, solar distillation systems have low operation and maintenance costs and require large installation areas and high initial investments. However, it is the best solution for remote areas and small communities in arid zones with lack of drinking water.

This paper concerns a study and theoretical analysis of solar still. It has been designed and installed in Mubi, Adamawa State of Nigeria, which has a great solar energy potential.

SYSTEM DESCRIPTION AND OPERATING PRINCIPLE

Figure 1 shows a schematic diagram of the designed solar still, which consists of a shallow triangular plastic basin. The inner part of the basin consists of an absorber plate made of galvanized steel and painted to form a matt black surface (absorptivity of about 0.98 and emissivity of about 0.08 from absorbed energy). The absorber plate is insulated from the bottom to prevent heat losses. Several thermometers were installed to measure the glass cover temperature, the water temperature and the ambient temperature. The top of the basin is covered with 3 mm thick transparent glass (transmissivity of about 0.88). The glass is tilted to the angle of latitude of Mubi, Adamawa State – Nigeria, 10° 15', to ensure maximum transmission of solar radiation into the still as well as enabling condensed vapor to trickle down the trough built in the still basin. The edges of the glass are sealed with headlamp gum so that the entire basin becomes air tight. The entire material is made of quality material designed to withstand the harsh conditions produced by water and sunlight and it is placed on a wooden stand. The design incorporates a supply fill port through which water is added into the still. Purified drinking water is collected from the distilled output collector. There is an overflow port, which will flow out excess water in the still.

The contaminated water is poured into the still to partially fill the basin through supply fill port. Care was taken in adding the water at a slow enough rate to prevent splashing onto the interior of the still glazing or overflowing into the collection trough. The solar radiation, I(t) after reflection and absorption by the glass cover is transmitted inside the still enclosure. This transmitted radiation, τ_g I(t) is further partially reflected, R'_w I(t) and absorbed, α'_w I(t) by the water mass. The attenuation of solar flux in water mass depends on its absorptivity and depth. The solar radiation finally reaches the blackened surface, generally known as the basin liner, where it is mostly absorbed. After absorption of solar radiation at the basin liner, most of the thermal energy is converted to water mass and a small quantity is lost to the atmosphere, by conduction. Consequently, the water gets heated, leading to an increased difference of water and glass cover temperatures. There are basically three modes of heat transfer, radiation, $\dot{q}_{rw}$; convection, $\dot{q}_{cw}$; and evaporation, $\dot{q}_{ew}$ from the water surface to the glass cover after releasing the latent heat. The condensed water vapor trickles down the inclined glass cover to an interior collection trough from there it is collected into the storage container through distilled output collection port. The thermal energy received by the glass cover, through radiation, convection and latent heat, is lost to the ambient by radiation and convection.

Theoretical analysis

In this section a complete mathematical model that describes the processes in the basin of the solar still is presented. These models will assist in determining the hourly saturated vapor pressures of water and glass, the convective and evaporative losses coefficients from the water surface to the glass, the distillate output and the instantaneous efficiency of the still.

Tiwari et al. (1989) explained the fraction of solar flux at different components of the still unit as shown in Figure 1 and mathematically expressed as:

Solar flux absorbed by the glass cover is

$$\alpha_g' = (1 - R_g)\alpha_g \tag{1}$$

Solar flux reflected by the water mass

$$R_w' = (1 - R_g)(1 - \alpha_g)R_w \tag{2}$$

Solar flux absorbed by the water mass

$$A_w' = \alpha_w'(1 - \alpha_g)(1 - R_g)(1 - R_w)\alpha_w \tag{3}$$

Solar flux absorbed by the basin liner

$$\alpha_b' = \alpha_b(1 - R_g)(1 - \alpha_g)(1 - R_w)(1 - \alpha_w) \tag{4}$$

Solar flux lost by the ambient, through water and glass cover, will be

$$L_a' = (1 - \alpha_b)(1 - R_g)(1 - \alpha_g)(1 - R_w)(1 - \alpha_w) \tag{5}$$

If the evaporation processes inside the still unit is considered as isobaric atmospheric process at thermal equilibrium, then all the absorbed solar radiation is utilized for evaporation and thermal losses. An energy balance for steady state around the water basin can be written as (Tamini, 1987):

Rate of Energy In = Rate of Energy Out
That is,

$$(\alpha_w' + \alpha_b')I(t)A_s = \dot{Q}_{ew} + \dot{Q}_{losses} \tag{6}$$

But

$$\dot{Q}_{ew} = \dot{m}_w L\,,$$

$$\dot{Q}_{losses} = U_L'(T_w - T_a)A_s \quad \text{and} \quad (\alpha_w' + \alpha_b') = (\alpha\tau)_w$$

Where:

Q_{ew} is the heat which is utilized by solar still for obtaining m kg of distilled water per m^2 per day;

U_L' is the overall heat transfer coefficient from water to ambient through top, bottom and sides of the still unit;

A_s is the area of the still;

T_w and T_a are the temperature of the water inside the still and ambient temperature respectively;

L is the latent heat of vaporization;

$\dot{m}_w$ is the daily output of the distillate.

Equation (6) can now be written as

$$\dot{Q}_{ew} = \dot{m}_w L = (\alpha\tau)_w I(t)A_s - U_L'(T_w - T_a)A_s \tag{7}$$

The heat transfer occurs outside the still, from the glass cover and the bottom and side insulation. Heat transfer within the still is referred to as internal heat transfer mode which consists of radiation, convection and evaporation as shown in Figure 1.

The external heat transfer, radiation and convection losses from the glass cover to the outside atmosphere q_g can be expressed as

$$q_g = q_{rg} + q_{cg} \tag{8}$$

Where;

$$\dot{q}_{rg} = \varepsilon_g \alpha (T_g^4 - T_s^4) \tag{9}$$

And

$$\dot{q}_{cg} = h_{cg}(T_g - T_a) \tag{10}$$

Where;

T_g is the temperature of the glass and may be assumed to be uniform due to the small thickness of the glass cover;
T_s is the sky temperature;
ε_g is the emissivity of glass cover;
σ is the Stefan – Boltzmann constant;
h_{cg} is forced convective heat transfer coefficient from the glass to ambient air.

Equation (9) can also be written as

$$\dot{q}_{rg} = h_{rg}(T_g - T_a) \tag{11}$$

with

$$h_{rg} = \varepsilon_g \alpha \frac{(T_g^4 - T_s)}{(T_g - T_A)} \tag{12}$$

By substituting equations (11) and (10) into equation (8) gives

$$\dot{q}_g = h_{rg} + h_{cg}(T_g - T_a) = h_{1g}(T_g - T_a) \tag{13}$$

For the effect of free convection and radiation from the glass cover, h_{1g} is given as (Watmuff et al., 1977):

$$h_{1g} = 5.7 + 3.8v \tag{14}$$

Where; v is the wind speed in m/s.

In case the radiation and convective losses are to be evaluated separately, the radiative heat transfer coefficient, h_{rg} can be obtain from equation (12) and the convective heat transfer coefficient, h_{cg} can be obtain from the relation (Watmuff et al., 1977)

$$h_{cg} = 2.8 + 3.0v \tag{15}$$

Heat is also lost from the water in the basin to the ambient through the insulation and subsequently by convection and radiation from the bottom or side surface of the still.

The bottom loss coefficient, U_b can be written as

$$U_b = \left(\frac{1}{h_w} + \frac{1}{h_b}\right)^{-1} = \left(\frac{1}{h_w} + \frac{1}{k_i / L_i} + \frac{1}{h_{cb} + h_{rb}}\right)^{-1} \tag{16}$$

Where; k_i and L_i are the thermal conductivity of air and the insulation thickness respectively.

The side heat loss coefficient, U_s can be approximated as

$$U_s = U_b \frac{A_{ss}}{A_s} \tag{17}$$

Where; A_{ss} is the surface area in contact with water and A_s is the area of the basin of the still. U_s can be neglected if $A_{ss} << A_s$.

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

$$\dot{q}_b = h_b(T_b - T_a) \tag{18}$$

Where;

$$h_b = \left(\frac{L_i}{k_i} + \frac{1}{h_{cb} + h_{rb}}\right)^{-1} \tag{19}$$

The internal heat transfer mode, that is, the heat exchange from the water surface to the glass cover inside the still unit is governed by radiation, convection and evaporation. In this case, the water surface and the glass cover are considered as infinite parallel planes. The rate of radiative heat transfer, $\dot{q}_{rw}$ from the water surface to the glass cover for these infinite parallel planes is given by

$$\dot{q}_{rw} = \varepsilon_g \sigma (T_w^4 - T_g^4) \tag{20}$$

$$\dot{q}_{rw} = h_{rw}(T_w - T_g) \tag{21}$$

Where; h_{rw} is the radiative heat transfer coefficient from the water surface to the glass cover and is given by (Watmuff et al., 1977).

$$h_{rw} = \varepsilon_g \sigma \left[(T_w^2 + T_g^2)(T_w + T_g + 546)\right] \tag{22}$$

Here T_w and T_g are measured in Kelvin.

Heat transfer occurs across humid area in the distillation 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 the fluid. Hence, the rate of heat transfer from the water surface to the glass cover, $\dot{q}_{cw}$ by convection is the upward direction through the humid fluid and can be estimated by

$$\dot{q}_{cw} = h_{cw}(T_w - T_g) \tag{23}$$

The convective loss coefficient from the water surface to the glass h_{cw} is given as (Dunkle, 1961)

$$h_{cw} = 0.884\left[T_w - T_g + \frac{(P_w - P_g)T_w}{268.9x10^3 - P_w}\right]^{1/3} \tag{24}$$

Where; P_w and P_g are the saturation partial pressures of water at water temperature and glass temperature, respectively.

The mass transfer coefficient, h_e, in terms of convective heat transfer coefficient h_{cw} (equation (24)) is given by (Baum et al., 1970):

$$\frac{h_e}{h_{cw}} = \frac{L}{C_{pa}} \frac{M_w}{M_a} \frac{1}{P_T} \tag{25}$$

Table 1. Overall results of solar still taken over a period of 9 h in Mubi, Nigeria.

T (h)	I(t) (W/m^2)	V (m/s)	T_a (^{o}C)	T_w (^{o}C)	T_g (^{o}C)	P_w (N/m^2)	P_g (N/m^2)	h_{cw} (W/m^2 ^{o}C)	h_{ew} (W/m ^{o}C)	m_{ew} (kg/m^{2}h)	(T_w T_a)/I(t) (^{o}C/W)	η_i
07:00	452	0.10	27.0	29.2	27.6	4004.44	3657.58	1.1130	3.9264	0.0095	0.0049	1.39
08:00	475	1.05	28.1	30.6	28.5	4331.43	3849.28	1.1224	4.1935	0.0133	0.0053	1.85
09:00	541	1.80	28.8	34.9	30.4	5487.77	4270.49	1.1599	7.4117	0.0502	0.0094	6.16
10:00	820	2.30	30.0	47.1	35.2	10373.63	5561.03	2.3107	15.2070	0.2726	0.0209	22.07
11:00	1041	2.80	31.4	62.2	41.6	21395.54	7832.82	3.2475	34.7934	1.0796	0.0296	68.85
12:00	1238	3.40	31.6	69.0	45.0	29029.40	9329.15	3.3014	44.0987	1.5942	0.0302	85.49
13:00	1108	3.30	32.0	66.0	43.2	25411.54	8508.45	3.1751	38.3050	1.3155	0.0307	78.82
14:00	830	2.60	31.8	60.4	39.8	19694.32	7129.43	2.9565	29.3452	0.9106	0.0345	72.83
15:00	601	2.10	31.2	53.2	35.3	14010.09	5608.02	2.7050	20.6618	0.5571	0.0366	61.54
16:00	256	1.48	30.8	40.3	34.2	7119.02	5282.78	1.7897	5.6293	0.0517	0.0371	20.89

Where:
P_T is the total gas pressure;
M_w is the mass of water vapor;
M_a is mass of air and;
C_{pa} the specific heat per unit volume at constant pressure of the mixture.

The rate of heat transfer per unit area from the water surface to the glass cover can be obtained by substituting the appropriate values for the parameters in equation (25) (Malik et al., 1982). Thus;

$$\dot{q}_{ew} = 0.013 h_{cw} (P_w - P_g) \tag{26}$$

Cooper (1973) derived similar equation and is given as

$$\dot{q}_{ew} = 0.0162 h_{cw} (P_w - P_g) \tag{27}$$

Rearranging equation (27) gives

$$\dot{q}_{ew} = h_{ew} (T_w - T_g) \tag{28}$$

Where;

$$\dot{h}_{ew} = 16.273 x 10^{-3} h_{cw} \frac{P_w - P_g}{T_w - T_g} \quad \text{(Cooper, 1973)} \tag{29}$$

The values of P_w and P_g (for the range of temperature 10^{0}C - 90^{0}C) can be obtained from the expression (Fernandez and Chargoy, 1990):

$$P(T) = \exp\left(25.317 - \frac{5144}{T + 273} \right) \tag{30}$$

Where; P(T) is the saturated vapor pressure. The hourly yield of the solar still is given as:

$$\dot{m}_{ew} = h_{ew} \frac{(T_w - T_g)}{L} x 3600 \quad \text{(Tiwari et al., 1989)} \tag{31}$$

The thermal efficiency of solar still can be defined as the ratio of the amount of thermal energy utilized to get a certain amount of distilled water to the incident solar energy within a given time interval. Further, the instantaneous efficiency of the still unit η_i can be determined as follows:

$$\eta_i = \frac{\dot{q}}{I(t)} = \frac{h_{ew}(T_w - T_g)}{I(t)} x 100 \tag{32}$$

Where; I(t) is the amount of solar radiation within a given time interval.

RESULTS AND DISCUSSION

The resolution of equations presented in the theoretical analysis section were employed to determine the result shown in Table 1 after some measurements as the hours of the day change from after sunrise to sunset. The corresponding plots for the ambient, water and glass temperatures verses the time of the day are displayed in Figure 2. The curves are essentially quadratic with maxima occurring at 31.6, 69.0 and 45.0^{o}C for ambient, water and glass respectively. It was noticed that the temperatures of the water and glass increase to maxima due to different heat flows (by convection, radiation and evaporation), going up to the glass.

Figure 3 shows a plot of the hourly variation of saturated partial pressures of water at water and glass temperatures, while plots of convective, evaporative coefficients and distillate against time; and best characterization curves are shown in Figure 4. Variation of instantaneous efficiency with $(T_w - T_a)/I(t)$ is shown

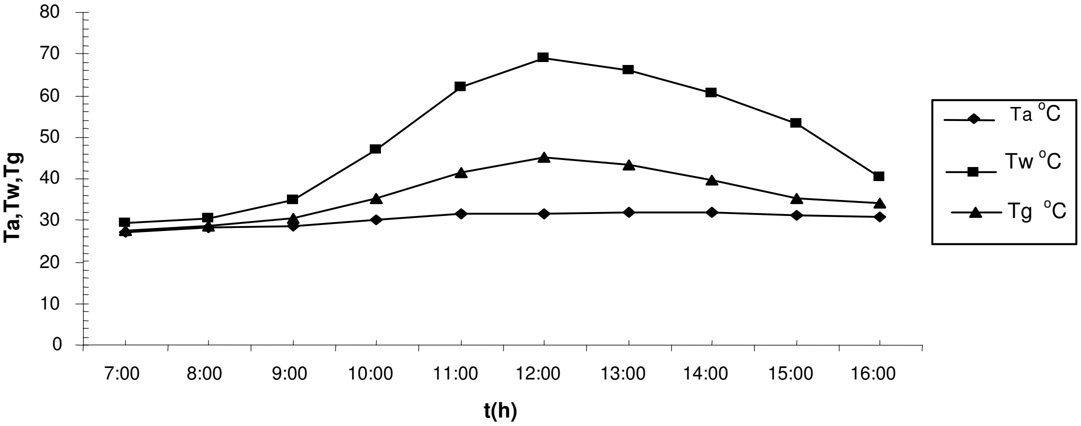

Figure 2. Ambient, water and glass temperature profiles over a 9 h period.

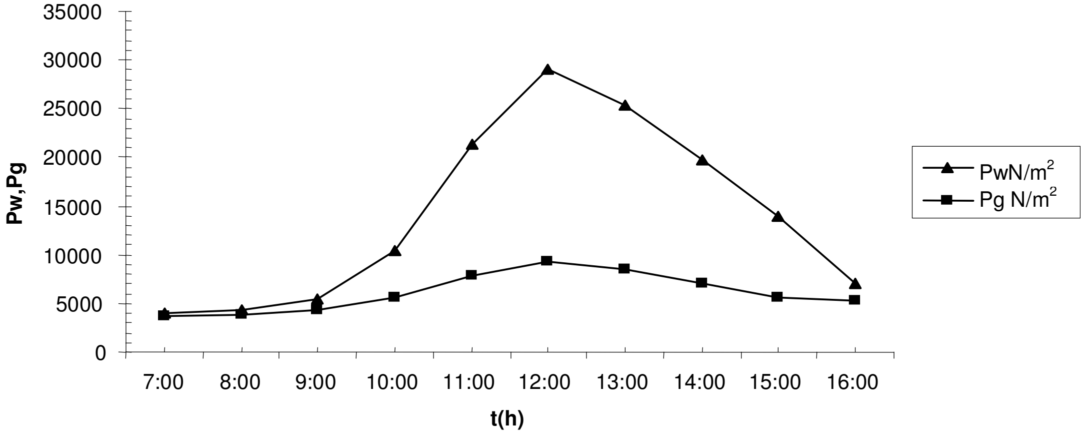

Figure 3. Hourly variation of saturated partial pressures of water at water and glass temperatures.

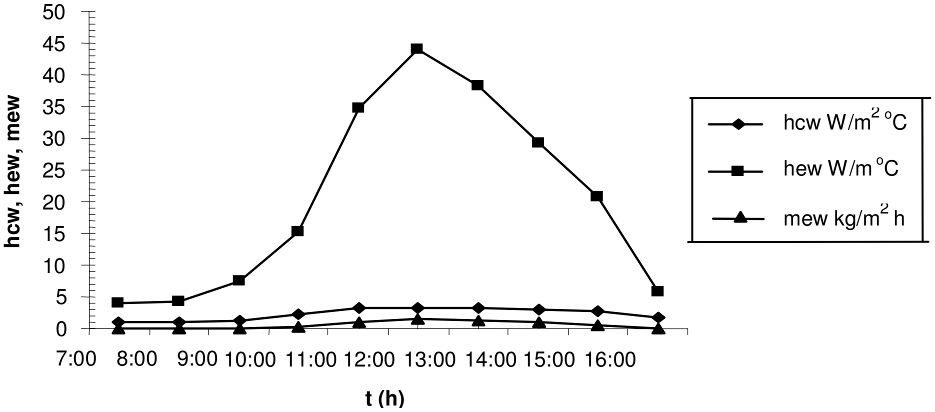

Figure 4. Convective, Evaporative coefficients and hourly distillate.

in Figure 5. A better efficiency of 85.48% has taken place at 12:00 h, which can be explained by the existing, at this time, of a better intensity of solar radiation (1238 W/m^2) as well as a better temperature of the feed water (69.0°C) yielding an important quantity of distillate water of about 1.5942 kg/m^2h (Figure 4). Figure 6 shows the

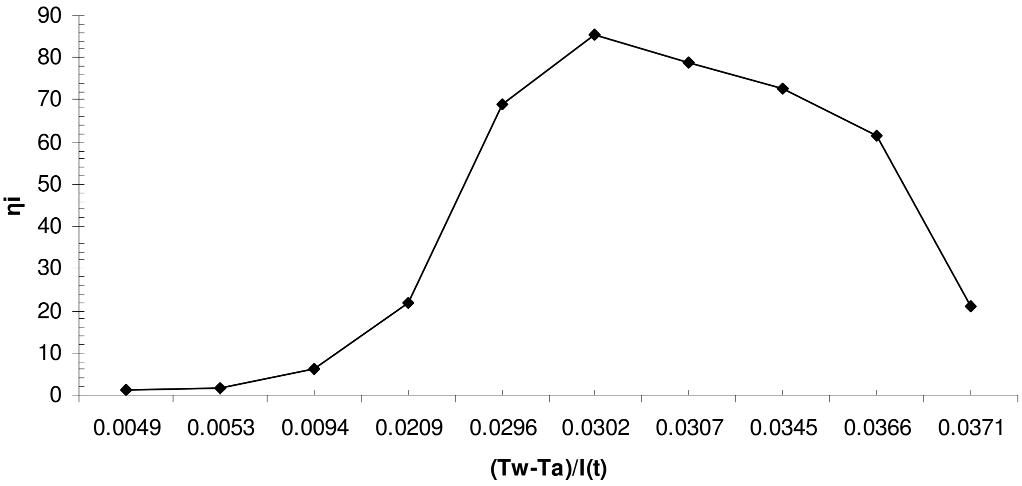

Figure 5. Variation of the instantaneous efficiency with $(T_w - T_a)/I(t)$.

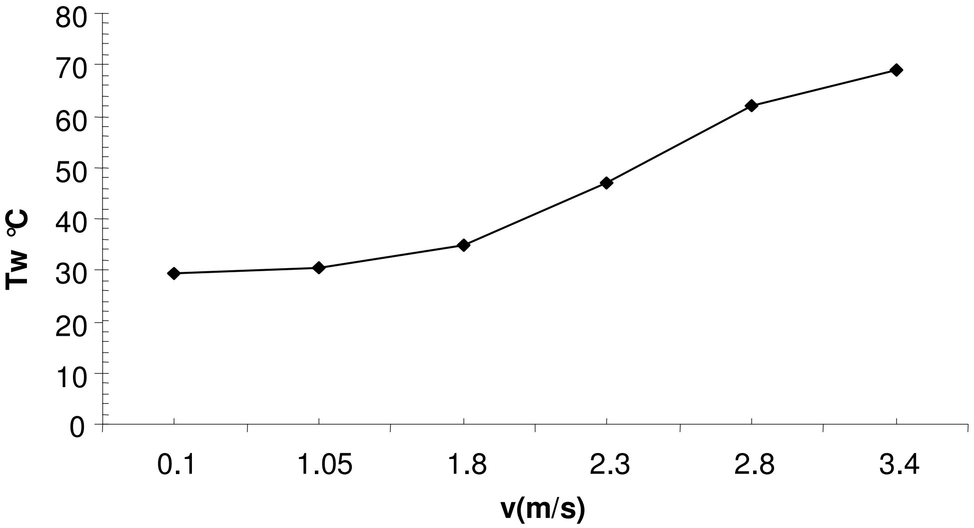

Figure 6. The impact of the wind velocity on the temperature of water inside the still.

variation of temperature of water inside the still with the wind velocity taken from 7:00 – 12:00 h. The increasing in wind velocity, leads to an increasing production in distilled water, as well as to a better cooling of the inner and the outer glass sides, followed by an important temperature difference between the water and the inner side of the glass, where this difference is of great interest, as it represents the cooling agent of the glass and where the external heat losses by convection can reach their maximum, as the coefficient of external heat exchange is dependent on the wind velocity according to the relation in equation (14).

The experimental result of distillate of water from the constructed still is presented in Figure 7. The productivity of distillate water corresponds favorably with the theoretical analysis obtained in Figure 4. Their maxima taken place at 12:00 h, where solar radiation intensity and the temperature of water inside the still are high, are 1.6 and 1.5942 kg/m^{2}h for practical and computed values respectively giving an efficiency of 99.64%.

Conclusion

A solar still was constructed and studied under actual environmental conditions of Mubi, Adamawa State of Nigeria. It is an economical means to provide portable water for remote areas and small communities in arid

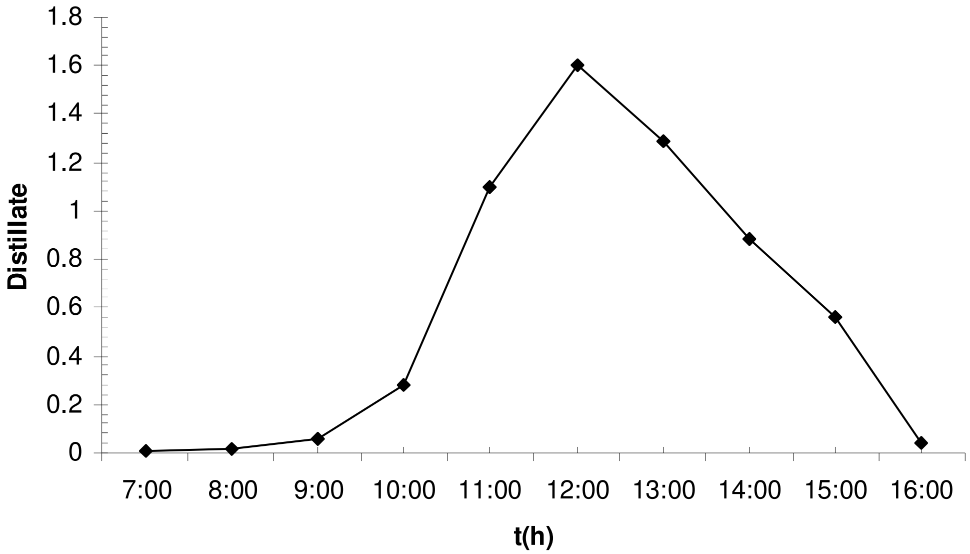

Figure 7. Distillate flow rate verses time.

zones. Theoretical analysis of heat and mass transfer mechanisms inside the still has been developed. Experimental investigations on the distillation performance of the solar still have been carried out. The experimental results obtained show that it corresponds favorably with the theoretical analysis and the productivity of the still increases with the intensity of solar radiation and the temperature of feed water. The results show that the system has distillation efficiency of 99.64% as compared to the theoretical analysis.

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