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Preliminary Experimental Study of a Single Slope-Double Effect Solar Still Incorporating a Phase Change Material

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***Abstract*— The performance of a double effect solar distillation unit incorporating a paraffin wax has been studied experimentally under the climatic conditions of Owerri, South-East Nigeria. The system comprises double basins with an absorber area of 1.10m^2 and a saline water storage tank. It was positioned in the North-South direction with both upper and lower glazings inclined at the latitude of the study location. Performance evaluation of the system was conducted for an extended period of time, capturing both diurnal and nocturnal phases of the system's operation. The hourly distillate yields of the upper and lower basins were compared. The lower basin performed better than the upper basin during diurnal phase. The diurnal distillate yield of the system ranged from 0.415L to 0.741L for the lower basin and zero to 0.025L for the upper basin. The system achieved a maximum distillate yield rate of 0.21 L/h and an average efficiency of 11.71%.*

I. INTRODUCTION

Rises in global mean air temperatures, ocean temperatures and sea levels are evidences of global climate change. This has led to the reduction in available freshwater quantity and thus, there is need to improve environmentally friendly ways of producing freshwater. The act of collecting dew to produce freshwater is probably as old as humanity. The ancient Greek sailors in the 4th century B.C., were said to have produced freshwater from the evaporation of seawater [1]. Desalination technology was used during the Second World War to produce potable water from brackish water due to the acute scarcity of freshwater [2]. Desalination process involves the removal of microbes, salt and other dissolved substances from saline water. During a desalination process, saline water is introduced into a process equipment and energy in the form of heat, pressure or electricity is applied, to produce desalinated water and concentrated brine [3]. Desalination processes can be grouped into two distinct categories, namely, phase change process (thermal driven) and single-phase process (membrane separation). In phase change process, heat is utilized to evaporate saline water, which later condenses to produce freshwater. In single-phase process, membrane is used in separation of freshwater from saline water [4]. Solar energy serves as an important energy source especially in rural areas without access to grid electricity supply, albeit with low efficiency. Solar thermal distillation system comprises a solar heat collector and a distiller. If the heat is provided by a separate solar collector, it is known as indirect process. If all components are integrated into the distillation plant, it is referred to as direct process.

Conventional solar still was first introduced by Charles Wilson in 1872 in Chile [5]. The system was in operation for forty years. It had a total distillation area of 4,700m^2 and a production capacity of 4.9kg/m^2 [6]. Ugwuoke et al. [7] conducted a performance evaluation of a solar water purifier made with glass fiber structure. The solar still was tested at Nsukka, Nigeria from November 2013 to December 2013. The maximum and minimum distillate yields recorded on the 4th day of the experiment were 1.1 liters at 14:00-16:00 hours and 0.2 liters at 08:00-10:00 hours respectively. Gan et al. [8] developed a novel solar distillation kit using a fiber rich paper coated with carbon black as its wick material. The system recorded efficiency of 88% and a production rate of $1.28kg(m^2h)^{-1}$. Using transparent Perspex condensing cover and a reflective mirror of area 0.18 m^2, Eze et al. [9] constructed a solar still of $0.6m^2$ absorber area for the purification of Lagos bar beach water. The system recorded a distillation efficiency of 36.8%. Ozuomba et al. [10] fabricated and tested a solar distillation kit in Owerri. The system recorded a mean daily production of $0.09m^3$ for an absorber area of $0.16m^2$. Aburideh et al. [11] studied the performance of a double slope solar desalination unit with an absorber area of $1.39m^2$. The system recorded an average daily productivity of $4L/m^2$. The accumulation of dissolved particles left behind in the basin of a solar still during desalination leads to the corrosion of the absorber plate and serves as a performance inhibitor. In order to overcome this shortcoming, Umar et al. [12] examined a single slope solar distillation unit of an absorber area of $0.35m^2$; modified with a 4-inch air tight hand hole at the side wall. Freshwater yields of $1.46L/m^2$ and $1.66L/m^2$ were recorded for the system with and without the modification respectively. However, the inclusion of the modification enabled the removal of the accumulated residues thus, minimizing basin corrosion.

Suneja et al. [13] compared the performances of a distillation unit having double basins but with the absorber inverted and another unit with normal absorber position. Observation showed that the unit with the absorber inverted performed better than the conventional unit. Madhlopa [14] investigated the performance of solar distillation system with triple basins, comprising an evaporation unit and two condensation units. The system recorded a total freshwater amount of $4.599kg/m^2$, as well as efficiency of 39%. This represented a performance improvement of 22% over a single basin solar still. Hashim [15] conducted a performance comparison of double and single basin solar distillation units and observed an improvement of 11% by the double basin type. The performance further improved by 32% with the addition of external reflectors. Nithin and Hraiharan [16] achieved a daily freshwater production of 5.2 kg/m^2 with a double basin solar still attached to a flat-plate solar collector. Ahmed et.al. [17] studied the performance of a three-stage evacuated solar distillation unit. At a pressure of 0.5bar, the system recorded daily freshwater yields of $6kg/m^2$, $4.3kg/m^2$ and $2kg/m^2$for the first, second and third stages, respectively. A marked reduction in production was observed with increase in pressure. Elsharif and Mahkamov [18] conducted a simulation of an evacuated multi-effect solar still with the aid of Matlab/Simulink. The system recorded freshwater yields of $39.9kg/m^2$ and $25.95kg/m^2$ at 0.03bar and atmospheric pressure respectively. Dutt et al. [19] observed that the flow of water at a low rate over the lower condensing surface of a double effect solar still improved the overall performance of the system. Al-Hinai et al. [20] evaluated the performances of single and double basin solar stills and observed an average annual distillate yields of $4.15kg/m^2$ and $6.1kg/m^2$ for the single and double basin stills respectively. Kumar et al. [21] conducted a configuration optimization of an evacuated multi-stage solar distillation system. Optimum performance of $28.04kg/m^2$ was found for a four-stage system. With an operating pressure of 0.03bar, the system recorded a maximum freshwater yield of $53.21kg/m^2$. In this study, a double effect solar distillation unit with a paraffin wax placed below the absorber plate was fabricated and tested in Owerri, Nigeria.

II. PRINCIPLE OF OPERATION

The energy exchange processes within and around the system is shown in Fig.1.

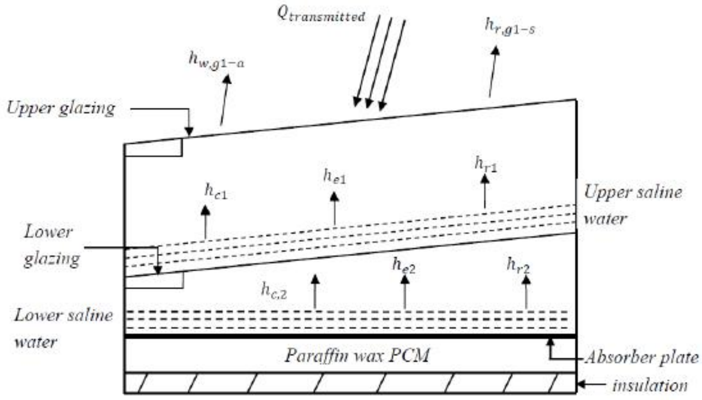

Fig.1: Energy exchange processes in a double effect solar still with a paraffin wax

The upper and lower glazings transmit the incident solar radiation to the absorber plate. The glazing system allows short wave radiation to pass through them but do not allow long wave radiation to go out, thereby acting as heat trap and as such, maximizing the absorber heat build-up. The absorbed thermal energy is transferred to the lower saline water and the paraffin wax below the absorber plate by convection and conduction respectively. The energy transferred to the lower saline water heats it thereby initiating evaporation. The air-vapour mixture rises to the underside of the lower glazing by convection where the evaporated energy is lost due to condensation thus leaving behind microbes, salts and other dissolved substances that were in the saline water. The condensate aided by gravity, drips down the lower glazing and is collected in a measuring trough. The released latent energy at the lower glazing plus the absorbed radiant energy, heats the upper saline water thus, initiating evaporation at the interface. Similarly, the resulting vapour loses its latent energy at the underside of the upper glazing and gets condensed in the process. The condensate flows into a measuring trough at the lower end of the upper glazing. The energy gained by the upper glazing is lost to the environment by radiation and convection to the sky and the ambient air respectively. The paraffin wax below the absorber plate is utilized during off-sunshine hours as the energy source and its duration is a function of the available mass.

The efficiency of a solar distillation system is expressed as the ratio of the released latent energy to the absorbed solar irradiance [5] and it is expressed mathematically as:

$$\eta_i = \frac{\dot{m}_p h_{fg}}{GA} \tag{1}$$

Where $\dot{m}_p$ is the rate of freshwater production, h_{fg} is the latent heat of vaporization of water per unit mass at the condensing surface, G is the solar irradiance flux and A is the area of the absorbing surface.

III. EXPERIMENTATION

3.1 SYSTEM DESCRIPTION

The system comprised upper basin, lower basin and a saline water feedstock tank. The saline water from the feedstock tank was fed into the upper and lower basins of the system through the connecting pipes regulated by valves as depicted in Fig.2.

Fig.2: Experimental setup of the double effect solar still with a paraffin wax underneath absorber

The upper glazing served as the condensing surface of the upper basin while the lower glazing served as both the base of the upper basin and the condensing surface of the lower basin. A 4kg paraffin wax placed below the absorber plate served as the phase change material. The lower and upper basins were housed inside a wooden box which served as insulation for the side walls and base of the solar still. The lower and upper glazings were inclined at the latitude of Owerri (N5.49^0). The test rig was positioned in the north-south direction at the Mechanical Engineering Workshop, Federal University of Technology, Owerri. The design parameters of the double effect solar distillation system are shown in Table.1

Table.1. Design specification of the double effect solar distillation unit

Component	Specification
Top condensing cover	Transparent glass (low iron)
Base of upper basin	Transparent glass (low iron)
Base of lower basin	Black galvanized steel
Phase change material	4kg paraffin wax
Absorber area	1.10m^2
Breadth of basin	1m
Length of basin	1.1m
Thickness of glazing	3.2mm
Angle of inclination of the upper and lower glazing	5.49^0

Combined front height of upper and lower basins	0.74m
Combined back height of upper and lower basins	0.836m

3.2 INSTRUMENTATION

The temperatures of the system components and the ambient air were measured using thermocouples. The thermocouples were linked to a data logger for automatic data capture while the system was in operation. The mean temperatures of the representative points of the components were captured and recorded on a memory card for an interval of five minutes. The recorded data were extracted from the data logger and transferred to a Microsoft excel worksheet. A Solar power meter with a measuring range of $0.1{\sim}1999.9W/m^2$ was used to measure the hourly solar irradiation on a horizontal surface at the test location. The surface wind speed was measured on an hourly basis with the aid of an anemometer placed at a height of 4m from the ground. The produced freshwater flowed through the outlet pipe to a measuring flask where the volume was measured and recorded. A schematic diagram of the thermocouple positions on the solar distillation unit is shown in Fig.3.

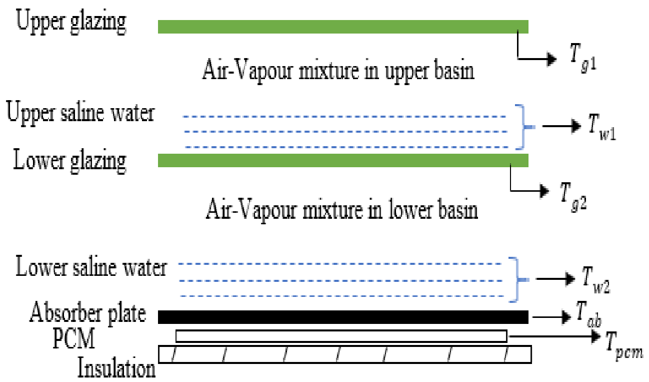

Fig.3: Positions of the thermocouples on the solar distillation unit

IV. RESULTS AND DISCUSSION

The results obtained from the experimental investigation for representative days of 28th January, 2nd March, 29th September and 10th October 2020 are presented in figures 4 to 13.

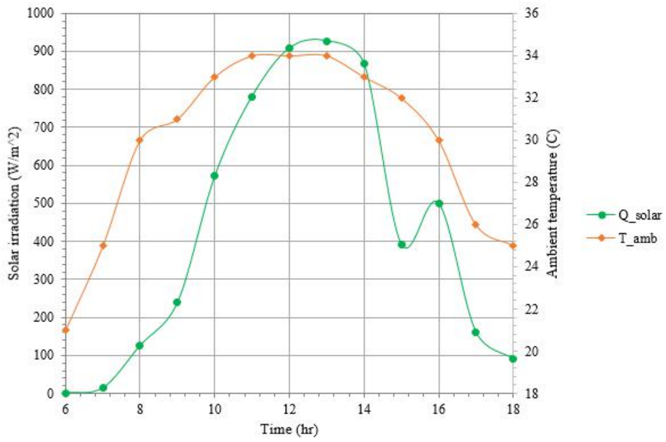

Fig.4: Solar irradiance vs ambient temperature in Owerri on 28th January, 2020

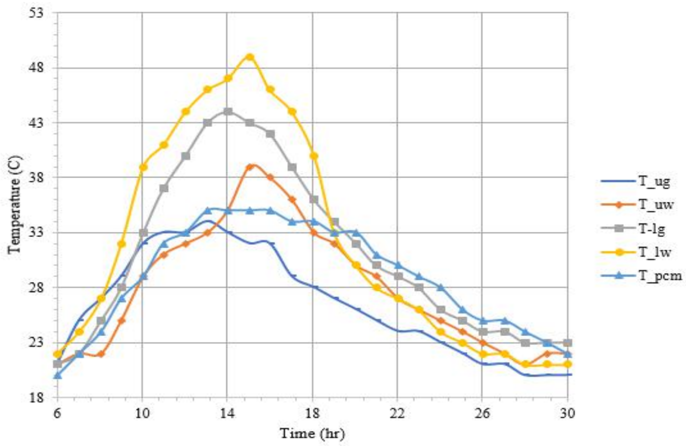

Fig.5: Twenty-four hours temperature profiles of the solar still components on 28th January, 2020

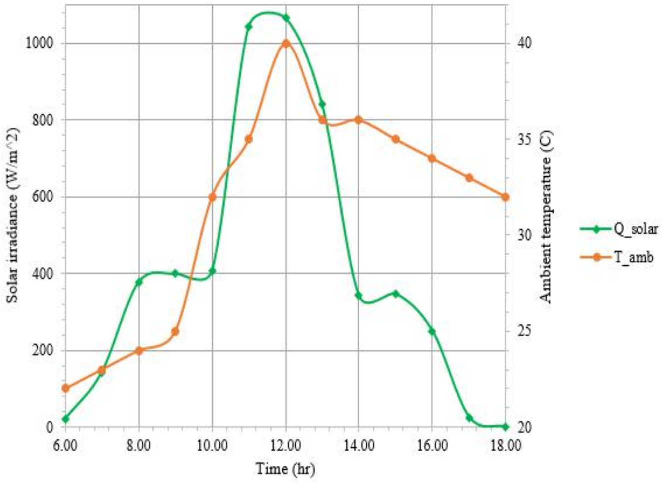

Fig.6: Solar irradiance vs ambient temperature in Owerri on 2nd March, 2020

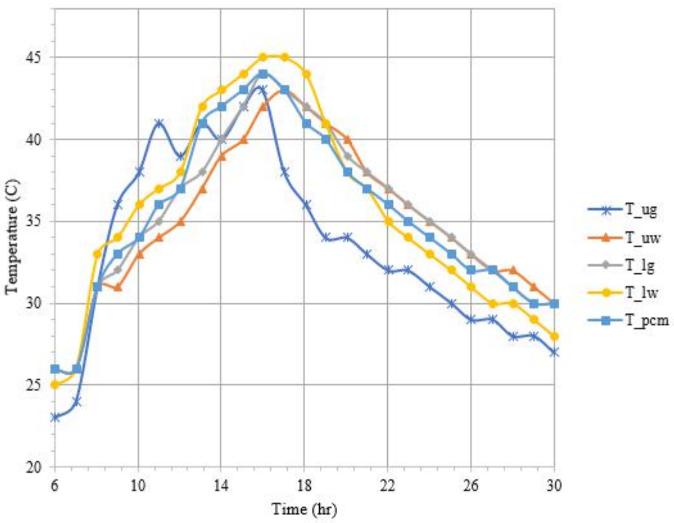

Fig.7: Twenty-four hours temperature profiles of the various still components on 2nd March, 2020

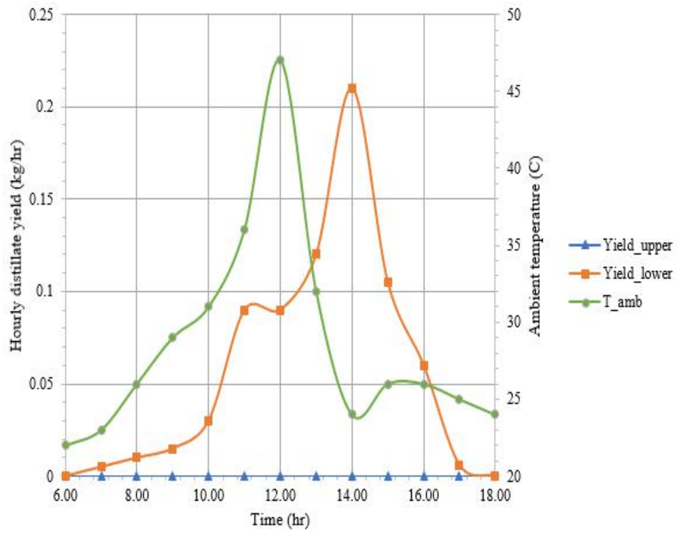

Fig.10: Diurnal variation of distillate yield vs ambient temperature on 29th September, 2020

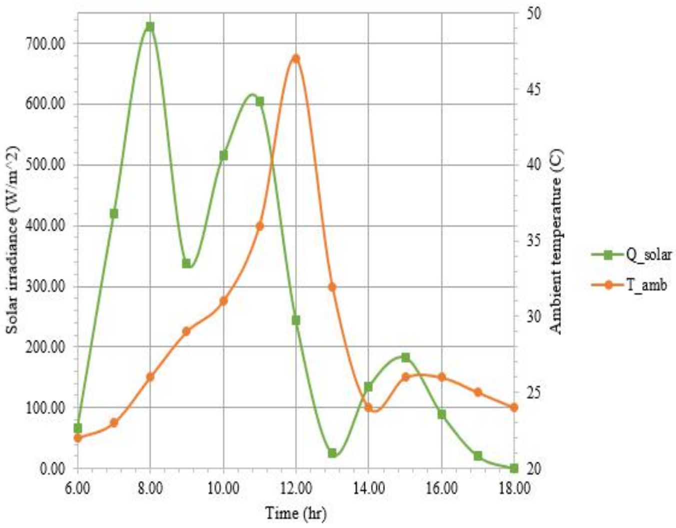

Fig.8: Solar irradiance vs ambient temperature in Owerri on 29th September, 2020

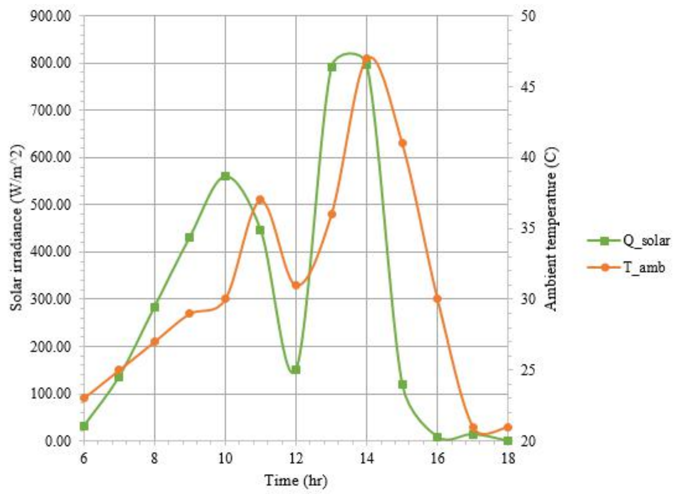

Fig.11: Variation of solar irradiance and ambient temperature In Owerri on 10th October, 2020

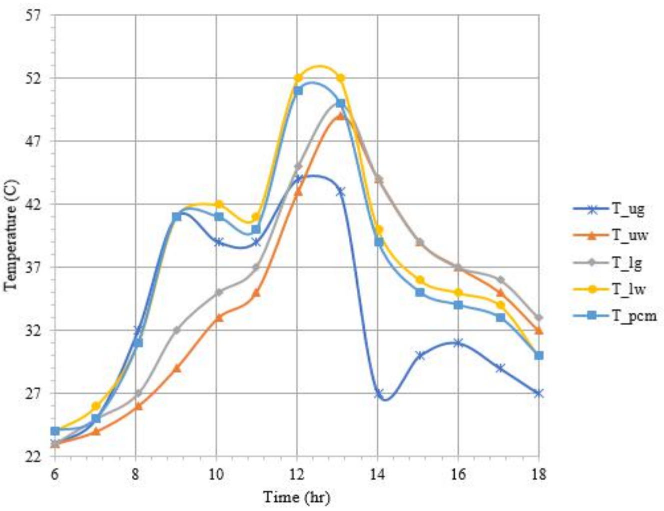

Fig.9: Diurnal temperature profiles of the solar still components on 29th September, 2020

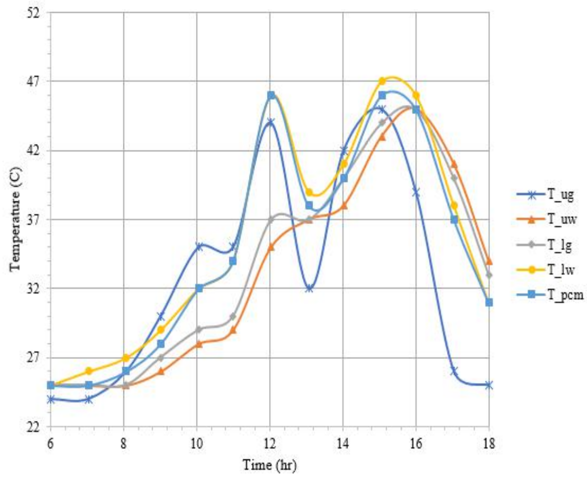

Fig.12: Diurnal temperature profiles of the solar still components on 10th October, 2020

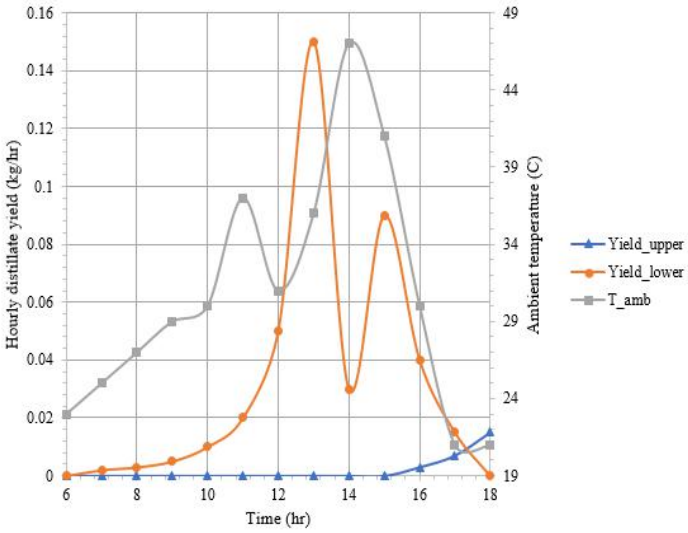

Fig.13: Diurnal variation of the distillate yield vs ambient temperature on 10th October, 2020

From figures 4 and 6, the solar irradiance peaked between the hours of 12:00pm to 13:00pm when the sun was vertically overhead [5]. From figures 8 and 11, the solar irradiance and ambient temperature showed significant fluctuations and peaked before and after noon respectively. The weather was cloudy with light shower on these test days. Figures 5 and 7 show the measured twenty-four-hours temperatures of the solar still components on 28/01/2020 and 02/03/2020 respectively. The components captured were: upper glazing, upper saline water, lower glazing, lower saline water and the PCM. The component temperatures varied in sympathy with the ambient temperature. The upper glazing was exposed to the ambient environment and as such, responded faster to changes in ambient conditions compared to the interior components. Thus, the peak of the upper glazing temperature lagged that of the ambient temperature. The PCM recorded lower temperature values compared to the interior components during the diurnal phase. During the early hours of the nocturnal phase, the PCM temperature declined the least and gradually attained the highest temperature within the solar still. At this point, the PCM functioned as the energy source thus, making the system sustainable for a given period. The interior components of the solar still achieved temperature values higher than the ambient values during the diurnal phase. This is due to the presence of the glass covers that are transparent to shortwave radiation and opaque to longwave radiation from the still interior. This phenomenon aided the internal heat retention of the system. Thus, the temperature of the exposed upper glazing reduced faster than that of the interior components and the lag between the interior component temperatures and the ambient temperature increased. Figures 9 and 12 show the measured diurnal temperature profiles of the still components on 29/09/2020 and 10/10/2020 respectively. The temperature of the still components and the ambient followed similar profile with the lower saline water attaining the highest temperature during the diurnal phase.

The amount of freshwater yield in a solar distillation unit much depends on the difference in temperature (positive) between the humid air and condensing surface. Thus, distillate production commences only when the humid air comes in contact with a condensing surface of lower temperature compared to the dew point temperature of the humid air [22]. From Fig.10, the upper basin recorded a zero freshwater yield while from figure 13; the lower basin commenced the production of freshwater ahead of the upper basin. This is attributed to the higher temperature values recorded by the upper glazing during the day and the poor absorptivity of the saline water and lower glazing. With the reduction in the solar irradiance intensity after attaining its peak, the upper glazing temperature dropped with subsequent improvement in the upper basin performance. Thus, the lower basin achieved a better diurnal performance compared to the upper basin. The upper glazing temperature dropped significantly during nocturnal period while the reduction in interior temperatures of the still components was hampered due to greenhouse effect. Thus, the upper basin achieved an improved freshwater yield during the nocturnal phase. From Fig.10, the hourly distillate yield of the lower basin varied in sympathy with the daily ambient temperature and attained its peak value after the ambient temperature. From Fig.13, the lower basin yield attained its peak value before the ambient temperature. The ambient temperature on 10/10/2020 showed some degree of fluctuations and attained its peak two hours after noon. At this point, the temperature potential between the lower saline water and lower glazing was already on the decline and as such attained its peak value ahead of the ambient temperature. The lower basin of the system recorded maximum distillate yield rates of 0.21 L/h and 0.15 L/h at 13:00PM on 29th September and 10th October, 2020 respectively. The productivity of the system for two distinct test days is shown in Table.2

Table.2: Diurnal performances of the upper and lower basins

S/No	Dates	Upper basin diurnal yield (L/day)	Lower basin diurnal yield (L/day)
1	29/09/2020	0	0.741
2	10/10/2020	0.025	0.415

The efficiency of the system for two test days was computed with the aid of Equation (1) and is presented in Table.3.

Table.3: Diurnal efficiencies of the upper and lower basins of the double effect solar still

S/No	Days	Upper basin efficiency (%)	Lower basin efficiency (%)	Total efficiency (%)
1	29/09/2020	0	11.60	11.60
2	10/10/2020	0.66	11.16	11.81

V. CONCLUSION

The performance of a double effect solar distillation unit incorporated with a paraffin wax has been investigated under Owerri climatic conditions. The hourly distillate yields of the upper and lower basins were compared. The yield rate of both basins for the months of September and October were plotted at different time interval. It was observed that the lower basin commenced production of distillate ahead of the upper basin with the upper glazing registering higher temperature values than the lower glazing during the early hours of the diurnal phase. Thus, the lower basin performed better than the upper basin during the diurnal phase. With reduction in irradiation intensity, the upper glazing temperature dropped with subsequent improvement in the upper basin yield through the nocturnal phase.

From the diurnal temperature plots, the lower saline water achieved higher temperature values than the upper saline water due to direct contact with the absorber plate. The upper basin experienced improved temperature difference between the upper saline water and the upper glazing during nocturnal phase with subsequent improvement in freshwater yield. From the yield plots, it was observed that the lower basin's hourly yield assumed similar profile with the ambient temperature. The hourly yield attained its peak value behind the solar irradiance. This difference results from the resilience time for effective heat flow within the system. The diurnal distillate yield of the system ranged from 0.415L to 0.741L for the lower basin and zero to 0.025L for the upper basin. The system recorded an average efficiency of 11.71%.

NOMENCLATURE

η_i Efficiency of the solar still %

$\dot{m}_p$ Freshwater production kg/day

A Area of the absorber plate m^2

G Solar irradiance flux W/m^2

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