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Research Article

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Performance Evaluation of Single Slope and Double Slope Solar Stills Integrated with a Solar Pond in a Tropical Humid Climate

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Abstract This research work involves the construction and testing of two solar stills, the one a single slope still and the other a double slope solar still, which were integrated with a solar pond. The stills were inclined at 28^o and tested in Akure, Nigeria on latitude 7.25^{o}N, longitude 5.08^{o}E and elevation of 115 m. Both stills were covered with glass. Relative humidity sensor, data logger (CR1000), pyranometer (sky) and mercury-in-glass thermometer were used for data collection from the rig. Six locally destructive sensors were also built for sensing temperatures at different points in the rig. The maximum air temperatures obtained from the solar still integrated with solar pond was 43.7 ^{o}C at 15:00 for single slope and 45.7 ^{o}C at 16:00 for double slope. Minimum air temperatures obtained was 33.1 ^{o}C. The maximum water temperature in the solar pond was 34.3 ^{o}C at 17.00 whilst the minimum water temperature was 27.2 ^{o}C at 11:00. The single and double slope solar still maximum water temperatures were 39.1 ^{o}C at 17:00 and 36.5 ^{o}C at 15:00 respectively. Minimum water temperature obtained was 31.4 ^{o}C at 11:00 for single slope solar and 34.3 ^{o}Cat 11:00 for double slope. Maximum air temperature obtained was 27.8 ^{o}C at 16:00 and 24.4 ^{o}C at 11:00. Maximum ambient relative humidity obtained was 92.72% at 11:00 and minimum obtained was 80.72% at 15:00.Maximum solar intensity obtained over glass cover was 584 W/m^2 at 14:00, and over water was 612 W/m^2 at 14:15pm and minimum solar intensity obtained was 163 W/m^2 at 18:00 for glass and 163W/m^2 at 18:00 for water. Maximum wind speed obtained was 0.98m/s at 13:00 and the minimum obtained was 0.61m/s at 18:00.The average maximum distillate from the double slope solar still was 0.00515 liters and 0.004379 liters for the single slope solar still. It was thus evident that the double slope solar still was more efficient than the single slope solar still. Daily yield obtained from solar still integrated with pond was 1.25 liter/day.

Keywords Single slope, double slope, solar still, solar pond, renewable energy

Introduction

As a result of the danger posed to the environment by fossil fuels, the world is shifting towards low carbon energy to be powered by new energy sources [1]. Exploitation of renewable energy resources has been in the forefront of campaign throughout the world for the significant proportion of the world energy needs [2].

Renewable energy sources comprise energy mix of solar, wind, hydro, bio-mass, ocean waves and tides, and geothermal. They are "renewable" because they are regularly replenished by natural processes and are therefore in endless supply. They also can operate without adversely affecting the environment.

More than two-thirds of the earth's surface is covered with water. Most of the available water is either present as seawater or icebergs in the Polar Regions. More than 97% of the earth's water is salty; the remaining 2.6% is fresh water. Less than 1% fresh water is within human reach.

This small amount is adequate to support life and vegetation on earth. Nature itself provides most of the required fresh water, through the hydrological cycle [3].

Water scarcity is a growing problem worldwide. Scarcity happens when the fresh water demand is similar in size to the fresh water supply [4]. According to UNESCO [5], hydrologists define an area as being "water stressed" when the average annual freshwater supply drops below 1,700 m^3 per person and "water scarce" when water supplies are below 1,000 m^3 per person. When supplies are below 500 m^3, this is defined as "absolute scarcity."

Due to abundance of seawater, we should rely on desalination of seawater which is abundant in nature to solve the problem of water scarcity. The efficiency of solar still from literature is low, hence the integration of a solar pond. The productivity of single and double slope solar still can be increased by the integration of solar ponds.

Mini solar pond is constructed and contained is seawater which absorbs temperature due to salt content of the water. The salt helps in storing heat in the lower region by preventing losses by convection. These solar ponds are called 'salt gradient'. It consists of lower convective zone, non-convective zone and upper convective zone.

The productivity of single and double slope solar still can be increased by increasing the evaporation rate which can be increased by increasing the water temperature in the basin of the stills. In the present work, water temperature of single and double slope solar still is increased by supplying preheated saline water from mini salt gradient solar pond. Hourly distillate output from the single solar still integrated with the solar pond is compared with that of the double slope solar still integrated with solar pond of same size.

As water shortages become a major problem, both nationwide and globally, desalination will increasingly be required to meet growing demands for fresh water. Desalination technologies have developed rapidly during the past several decades for desalting a variety of raw waters (seawater, brackish ground water, industrial waste water). Among the desalination technologies, thermal desalination, including multi-stage flash distillation (MSF) and multi-effect distillation (MED), are the current leading desalination processes. In 1996, the total capacity of thermal desalination represented about 70 percent of the world total of seawater desalination plants [6]. Thermal desalination is an energy-intensive process.

As costs for energy rise and carbon emission reduction is legislated it becomes increasingly important to lower traditional energy requirements for desalination by making use of solar energy and/or low cost waste heat.

Maleb *et al.* [7], investigated the effect of cover geometry on the productivity of a modified solar still desalination unit. The modification consists of a light weight, black finished, slowly-rotating drum, which led to a sustainable, cost-effective, and low-tech amendment that preserves the key features of the still while considerably increasing its yield compared to a control still that does not include the drum. Three different cover geometries of the modified still were studied and the effect of cover design on the performance of the still in terms of measured temperatures and productivity was considered. The three cover designs are as follows: double-sloped or triangular, single-sloped and curved cover. It was observed that higher temperature differences between inside and outside cover did not correspond with a higher productivity and it could be noted that a lower water or system temperature did not imply a lower performance, which was especially true for the single-sloped system. Furthermore, no particular cover design performed best for all considered months yet all of the new systems gave a higher yield than that of the control. The average percent improvement varies between 200-300%. Future improvement of the system involves focusing on the off-shine hours and minimizing the cooling effect of the drum that might be occurring at night was recommended.

Edeoja *et al.* [8], investigated the effect of angle of cover inclination on the yield of a single basin still under Makurdi climate. Five single basin solar stills with varying angle of inclination of 4, 7, 10, 13 and 15^o with the covers having aperture area of $0.24m^2$. It was observed that optimum angle of inclination for simple basin solar stills for the location is greater than 15^o.

Kasede *et al.*[9], studied solar evaporative crystallization process at Lake Katwe using brine evaporation rates, thermal, convection, and radiation energy losses as well as reported meteorological data around the Salt Lake basin. A simulation model of a salt pan was developed on a lumped basis to study its behavior with the effects of the different factors affecting the evaporation process investigated.

Egbe *et al.* [10], worked on the design of Solar Pond which can be used for different applications such as desalination of water as source of clean water especially in countries likes Sudan, Mali and others places in Africa that are facing chronic water situation, providing hot water for domestic use, hot water industrial use and importantly it can be used to produce electricity.

Goutham and Krishna [11], made a research on solution for storing solar energy only by constructing a simple pool of salt water and reported that solar pond is a pool of salt water which serves as the solar energy collection and sensible heat storage, heat storing capacities and also the factors that influence the technical and the economic viability of the solar ponds were discussed.

Jayaprakash *et al*. [12], designed and analysed low cost solar still using transparent LDPE cover. Spherical solar still under climatic conditions and operational parameters in Coimbatore (11° N latitude), India. The performance of spherical solar still with two different thicknesses of low density polyethylene (LDPE) cover was analyzed. The spherical solar still was covered by low density polyethylene cover (LDPE) of thickness 0.176 and 0.107 mm respectively. The water temperature, air temperature, ambient temperatures were recorded at the regular intervals of time. The inside and outside of the cover temperatures are noted with solar radiation. The efficiency of the spherical solar still was analyzed for two thicknesses top cover. The internal heat transfer mode and external heat transfer mode are calculated. The hourly output yield per $m^2$of the still was calculated. It was observed that the average evaporation rate is more for less thicknesses of top cover than the higher thickness. This type of still is designed with low cost. The maximum efficiency obtained for this system is 22%. These analyses are also suggested as a method to produce a low cost distillation unit for acquiring high pure distilled water.

Lammayot *et al.* [13], worked on heat extraction from solar pond with thermosyphonic coils for salt production in Northeast Thailand. The solar pond has an area of 30 m^3. The thermophonic coil consisted of 15 U-shaped high density polyethylene (HDPE) tubes with a diameter of 25.4 mm. In this study, thermophonic flow can be used for the heat extraction system of the solar pond. it was demonstrated that the stored heat in solar pond can be used for 24 h by preheating the saline water in the storage tanks and gaining higher temperatures up to 24.14°C on average in the daytime; while, it can be increased up to 22.10°C at night.

A very large-scale process of solar distillation naturally produces fresh water. The essential features of this process are thus summarized as the production of vapours above the surface of the liquids, the transport of vapors by winds, the cooling of air–vapour mixture, condensation and precipitation. This natural process is copied on solar desalination. As the available fresh water is fixed on earth and its demand is increasing day by day due to increasing population and rapidly increasing of industry, hence there is an essential need to get fresh water from the saline brackish water present on or inside the earth. This process of getting fresh water from saline brackish water can be done easily and economically by desalination [3].

In the industrialized world, government policies increasingly emphasize the replacement of fossil energy by renewable, low-carbon energy, and so water-scarce regions such as North Africa, northern Nigeria may be considering solar-driven desalination systems as a supplement to existing fresh water supplies. Even in regions where petroleum resources are copious, such as Southern Nigeria *i.e.* Rivers State, Bayelsa state, Warri. Solar-driven desalination is attractive as a means of conserving fossil fuel resources and limiting the carbon footprint of desalination. Finally, in settings that are remote and “off the- grid,” a solar-driven desalination system may be more economical than alternatives such as trucked-in water or desalination driven by diesel-generated electricity [4].

Solar ponds may be classified into two main categories: non-convective solar ponds and convective solar ponds. A convective solar pond is usually a horizontal solar collector that normally consists of one homogenous liquid layer with a transparent cover on the pond’s surface. Non-convective solar ponds suppress heat loss by preventing convectional currents from developing within the liquid body. They usually consist of three saline water layers, where the salt concentration is highest in the bottom layer and lowest in the shallow surface layer.

Non-convective solar ponds are simple in design and can be constructed at reasonable cost; they can provide heat for domestic, agricultural, industrial and desalination purposes and they can also generate power [10].

Solar distillation systems are classified as passive and active solar stills. In the case of active solar stills, an extra-thermal energy by external mode is fed into the pond of passive solar still for faster evaporation. The external mode may be collector concentrator panel. Different types of solar still available in the literature are:

- Conventional Solar Stills
- Single-slope Solar Still with Passive Condenser
- Double Condensing Chamber Solar Still

- Vertical Solar Still
- Conical Solar Still
- Inverted Absorber Solar Still
- Multi-Wick Solar Still
- Multiple Effect Solar Still. [3]

Some of the basic parts of a simple solar still are supply fill port, overflow port and distilled output collection port [14]. A salt-gradient solar-pond collects and stores solar-insolation as heat in single unit. The stability of the solar-pond is normally maintained by the presence of the salt when exposed to solar insolation for heating [15]. Performance of solar still based on productivity, efficiency as well as internal heat and mass transfer coefficient. Hence performance of solar still is directly proportional to internal heat transfer coefficients. Internal heat and mass transfer coefficient in the solar still is based on three parameters called convection, radiation and evaporation, hence there are three heat transfer coefficient called convective heat transfer coefficient, radiative heat transfer coefficient and evaporative heat transfer coefficient. To increase the efficiency of solar still the evaporation rate should be increased and convective, radiative losses should be minimized [16].

Materials and methods

The double slope and single slope solar stills, shown in Plate 1, were integrated to a solar pond made of mild, 0.35m height and 1.25m in diameter resulting in the surface area of 0.2725m^{2}exposed to solar radiations. The stills were maintained at 0.05m water depth .The base of the stills were coated with a black paint to enhance evaporative efficiency. The inner boxes 60.00 cm x 60.00 cm were made of galvanized iron sheets. The outer boxes were made of 12.00 mm thick plywood and the spaces, 25.00 cm, between them were filled with dried saw dust as insulating material.

Seawater water was poured into the still to partially fill the basin. The glass cover allowed the solar radiation (short wave) to pass into the still, which was mostly absorbed by the blackened base. The water began to heat up and the moisture content of the air trapped between the water surface and the glass cover increases. The base also radiated energy in the Infra-red region (long-wave) which was reflected back into the still by the glass cover, trapping the solar energy inside the still (the greenhouse effect). The heated water vapor evaporated from the basin and condenses on the inside of the glass cover. In this process, the salts and microbes that were in the sea water were left behind. Condensed water trickles down the inclined glass cover to an interior collection trough and out to a storage bottle.

Solar pond (pre-heating reservoir) absorbed solar energy and trapped it. Preheating the seawater took place in the pond in order to improve the efficiency of the system. The pre- heated seawater passed through the hose by gravity into the solar still. The Solar Still received seawater from the solar pond. Evaporation and condensation processes which are the basics for desalination took place in the still. The clean water was condensed (film condensation from the glass) into the collector (trough) by gravity.

Type J thermocouple sensors having an accuracy of $\pm 2.2^{o}$C were used to measure the temperatures at 6 different locations on the experimental rig (Plate 1). These thermocouples were attached to a data logger which stored the readings. The thermocouples were used to record the condensing cover temperature, basin temperature, water temperature of both solar stills and the temperature in solar pond. The thermocouples were calibrated periodically. The distillate outputs were collected in a narrow necked bottle to minimize evaporation losses during collection of distillate. A graduated water measuring beaker of capacity 100 ml respectively was used for this purpose. The total radiation received on the condensing cover of still and solar pond was measured by a Pyranometer having a sensitivity of 17$\mu V/m^2$.

The solar still integrated with solar pond for desalination was fabricated using locally sourced materials. In order to find the effect of solar pond over single slope and double slope solar still, number of readings were taken on the experimental rig for 15 days in month of August 2018 in Akure, Nigeria.

Sea water has a salinity of approximately 3.5% which means for every 1 litre of seawater, there is 35g of salts. The salinity was maintained at 35g/litre for this experimental analysis.

Plate 2 shows the distillate output (A,B,C) for single slope and double slope solar stills whilst Plate 3 shows the locally made sensors (1C), wind speed (1B) were calibrated and connected to Data logger (CR1000) (1A). Digital Multi-meter (1D).

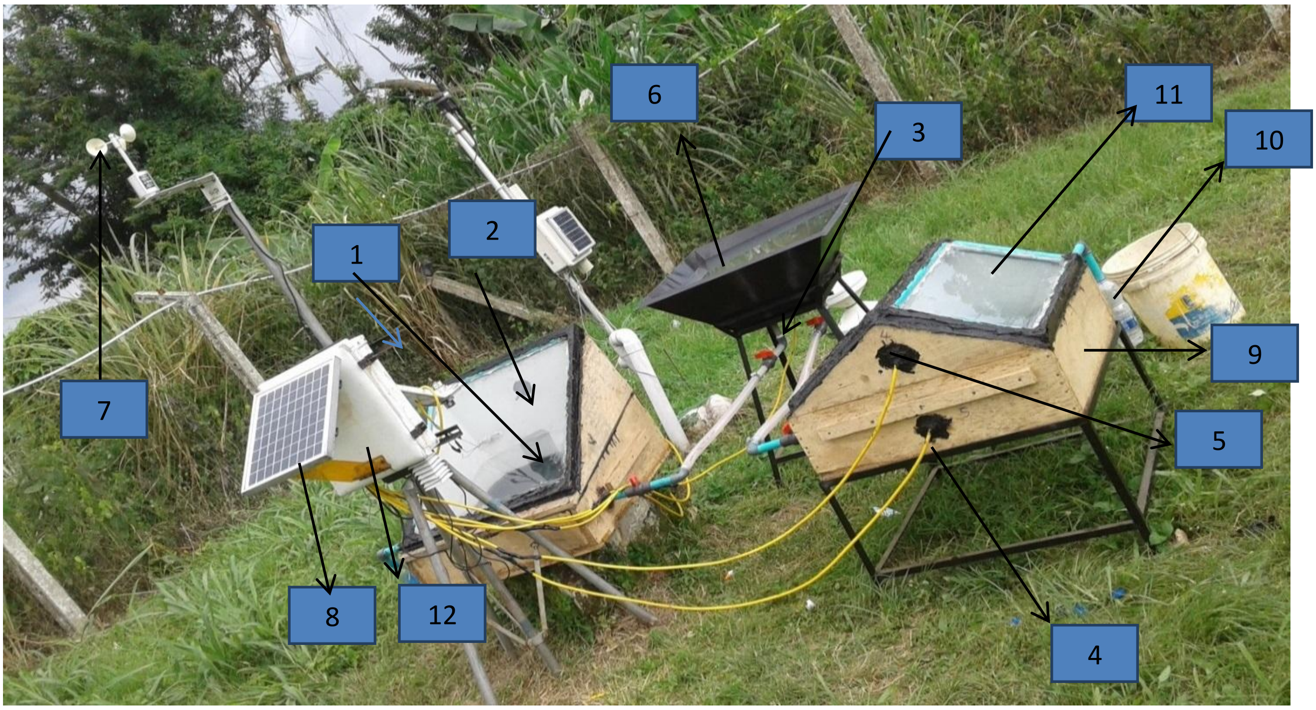

Plate 1: Single slope and double slope solar still integrated with solar pond for desalination with thermocouple locations 1,2,3,4,5. Solar pond (6), Wind speed (7), Solar energy absorber (8), Wood (9), Distillate container (10), Glass (11), Data logger housing (12).

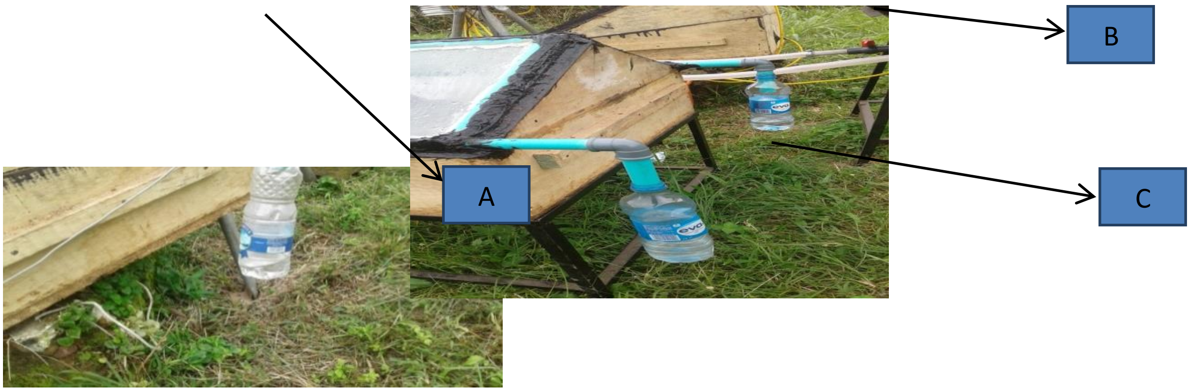

Plate 2: Distillate output (A,B,C) for single slope and double slope solar still

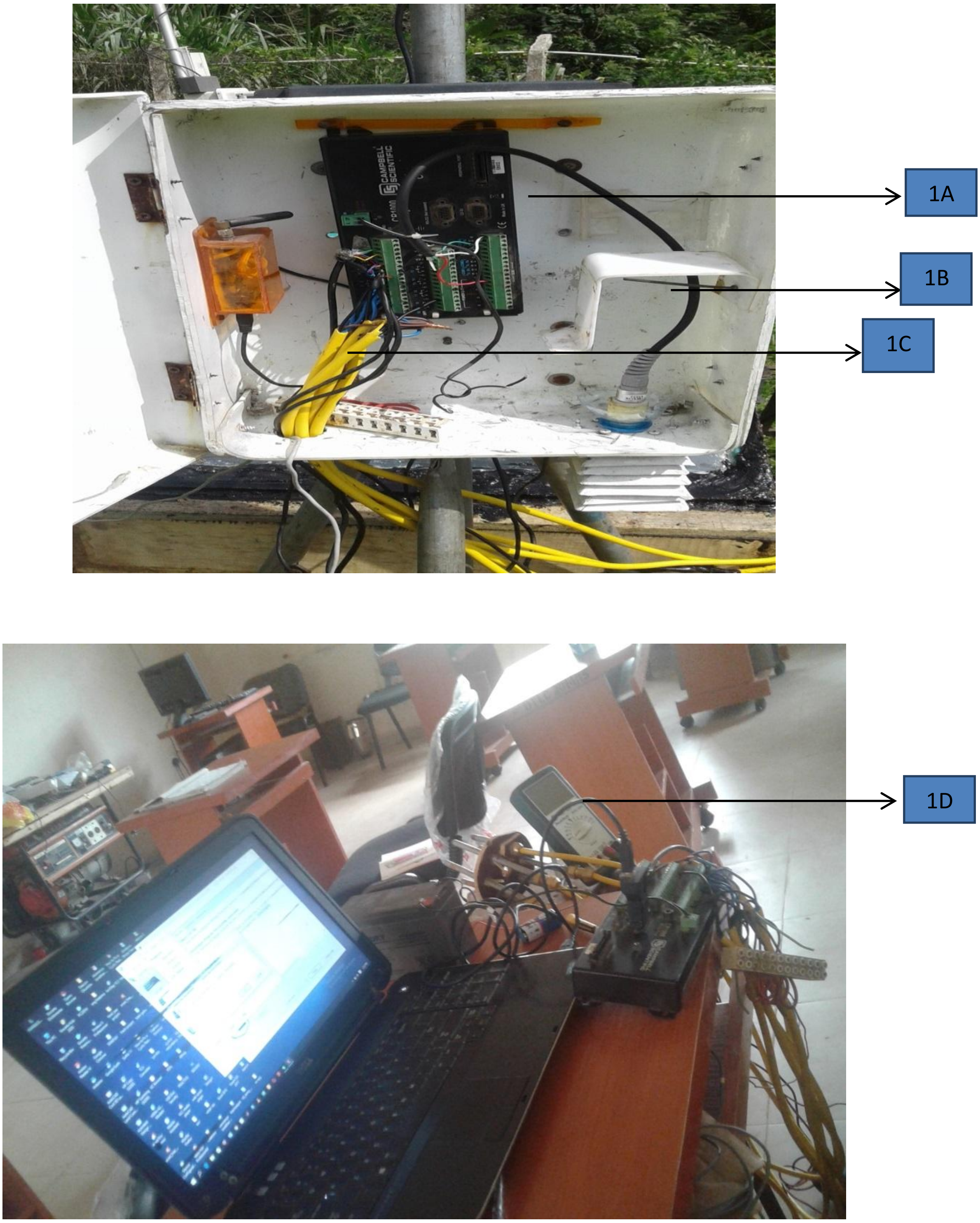

Plate 3: locally made sensors (1C), wind speed (1B) were calibrated and connected to Data logger (CR1000) (1A). Digital Multi-meter (1D).

Results and Discussions

Data were collected from the experimental rig for 15 days (August 6th 2018- August 21st 2018) from different points in the rig. The locally made sensors were connected to data logger for easy collection and collation of data. Also, the output (distillate) were collected from double slope and single slope solar still integrated with solar pond hourly respectively. The data collected from data logger and distillate collected were analyzed. Figure 1 shows the variation of productivity with respect to time of the day (hr) for double slope (DS) and single slope (SS) solar still integrated with solar pond

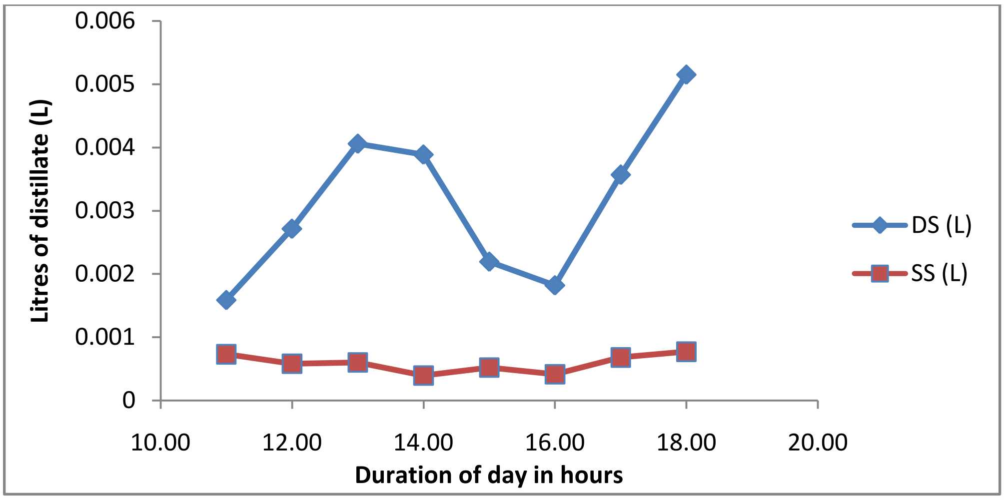

Figure 1: Variation of productivity with respect to time of the day (hr) for double slope (DS) and single slope (SS) solar still integrated with solar pond

Average maximum distillate output obtained from double slope solar still was 0.00515 liters while the minimum obtained was 0.001586 liters. Average maximum distillate obtained from single slope solar still was 0.000771 liters at 18:00 and minimum was 0.000393 liters.

The average maximum distillate of double slope solar still was 0.004379 liters more than thesingle slope solar still.

Figure 2 shows the variation of temperature of air, water in single slope Solar Still, double slope solar still, and solar pond.

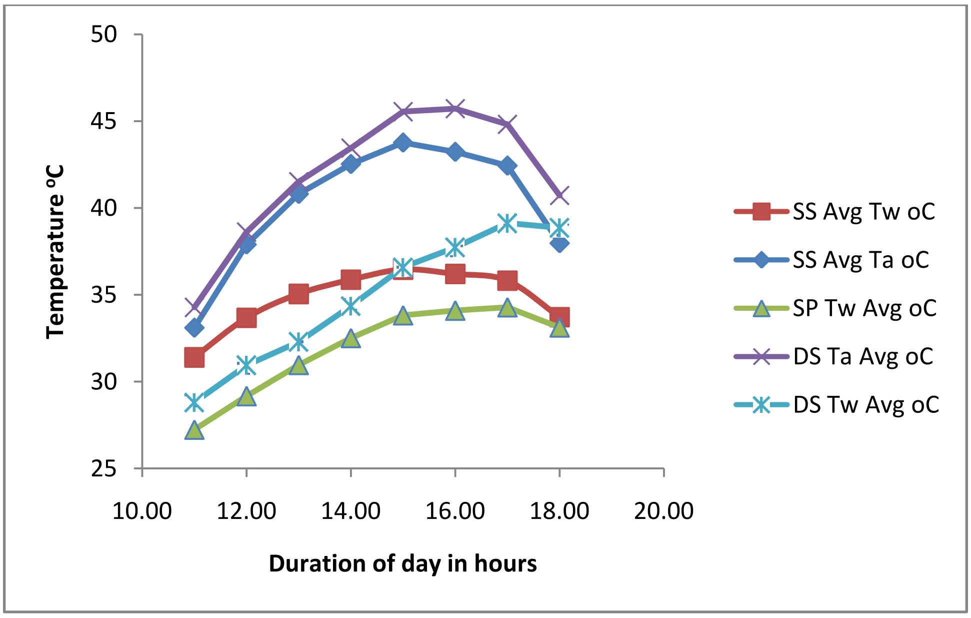

Figure 2: Variation of temperature of air and water at different points in single slope (SS) and double slope (DS) stills integrated with Solar Pond (SP) respect to time of the day

The Solar Still integrated with Solar Pond maximum air temperature obtained was 43.7 ^{o}C at 15:00 for single slope and 45.7 ^{o}C at 16:00 for double slope which was 2^{o}C more than single slope solar still. Minimum air temperature obtained was 33.1 ^{o}C at 11:00 for single slope and 34.3^{o}C at 11:00 respectively.

The maximum temperature of water from Solar Pond was 34.3 ^{o}C at 17.00 and minimum was 27.2 ^{o}C at 11:00. The Solar Still integrated with Solar Pond maximum water temperature obtained was 36.5 ^{o}C at 15:00 for single slope and 39.1 ^{o}C at 17:00 for double slope which was 2.6 ^{o}C more than single slope Solar Still. Minimum water temperature obtained was 31.4 ^{o}C at 11:00 for single slope Solar Still and 34.3^{o}C at 11:00 for double slope Solar Still.

Figure 3 shows the Variation of wind speed (ws) with respect to time of the day.

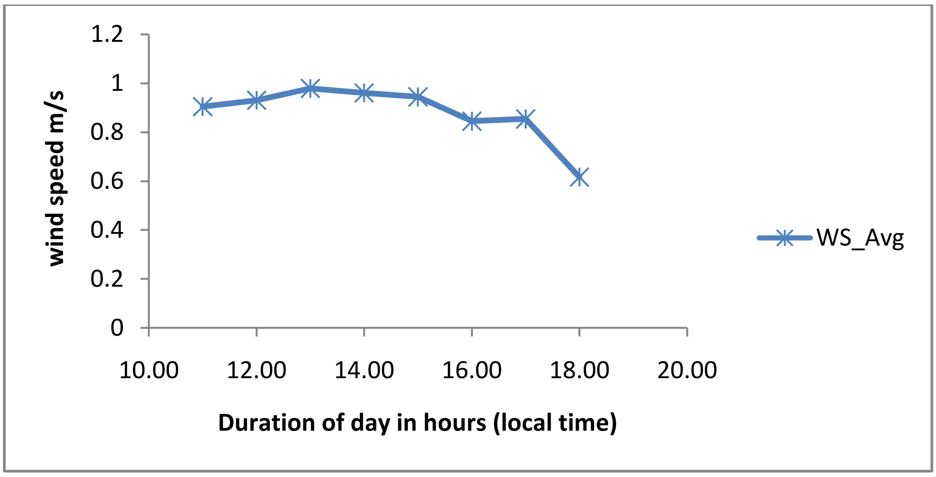

Figure 3: Variation of wind speed (ws) with respect to time of the day

Figure 4 shows the variation of Solar intensity of glass and water (net glass and net water), with respect to time of the day whilst Figure 5 shows the variation of ambient air temperature with respect to the time of the day. Figure 6 shows the variation of wind speed (ws) with respect to the time of the day.

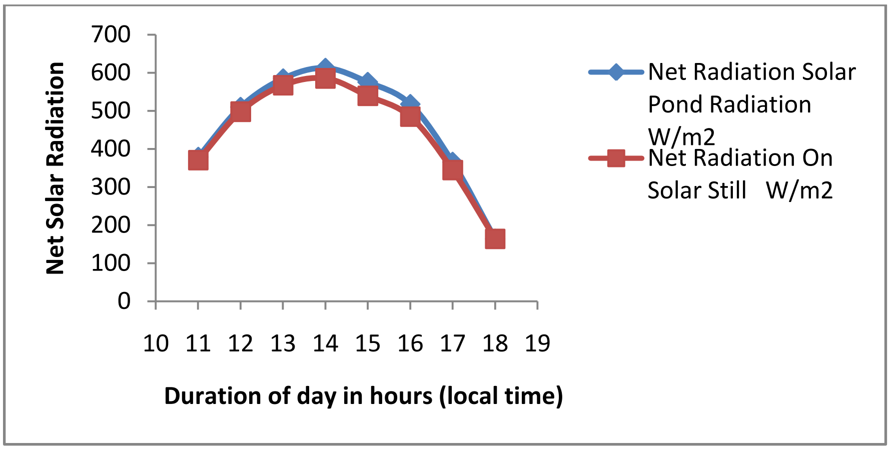

Figure 4: Variation of Solar intensity of glass and water (net glass and net water), with respect to time of the day

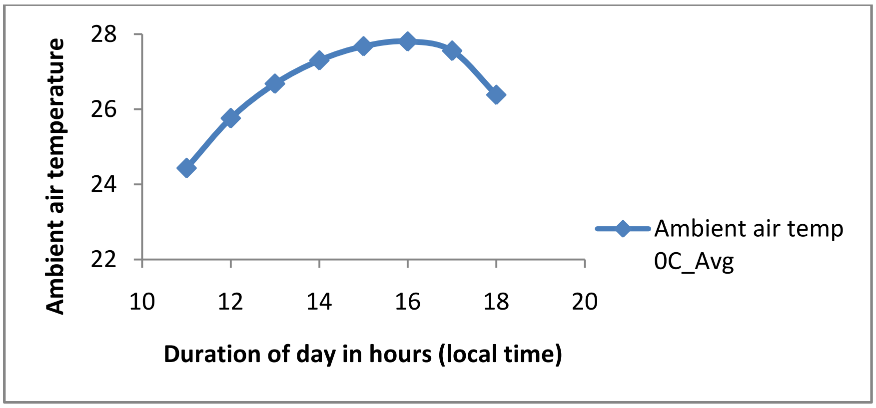

Figure 5: Variation of ambient air temperature (airtc) with respect to time of the day

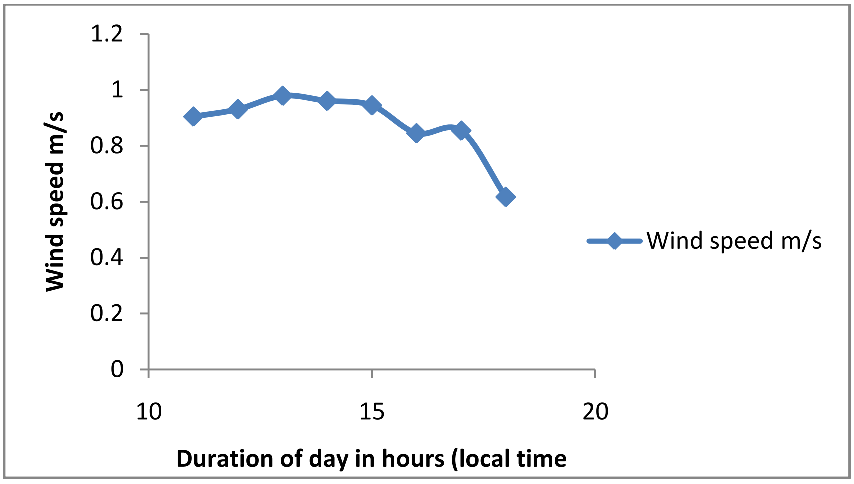

Figure 6: Variation of wind speed (ws) with respect to time of the day.

Maximum Air temperature obtained was 27.8^{o}C at 16:00 and 24.4^{o}C at 11:00. Maximum ambient relative humidity obtained was 92.72% at 11:00 and minimum obtained was 80.72% at 15:00.

Maximum solar intensity obtained over glass cover was 584 W/m^2 at 14:00, for water was 612 W/m^2 at 14:15 and minimum intensity obtained was 163W/m^2 at 18:00 for glass and 163W/m^2 at 18:00 for water. Maximum wind speed obtained was 0.98m/s at 13:00 and minimum obtained was 0.61m/s at 18:00.

Conclusion

A solar pond integrated with Solar Still (double slope and single slope) system for desalination of seawater was designed and constructed. The output of distillate from the Solar Still was increased by increasing the evaporation rate and by minimizing the convective and radiative losses in Still. A mini Solar Pond was used to preheat the saline water used in the Solar Still. The evaporation rate can be increased effectively by pre-heating the inlet water of Still. Performance of the single slope and double slope Solar Still integrated with the Solar Pond was evaluated and the two type of Stills were compared. The average maximum distillate of double slope Solar Still was 0.00515 liters and 0.004379 liters for the single slope Solar Still. It is evidently the double slope Solar Still was more efficient than the single Solar Still. Double slope Solar Still was more efficient in terms of distillate output because of the orientation. Daily yield obtained from solar still integrated with pond was 1.25 liter over 24 hrs.

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