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Research Article

Investigation of Some Factors that Lead to Improved Performance vis-à-vis the Efficiency of Single Basin Solar Stills

Charles N. O. Kwach,¹ Reccab M. Ochieng,² and Frederick N. Onyango²

¹Office of the Registrar Academic Affairs, Maseno University, P.O. Box 333, Maseno 40105, Kenya

²Department of Physics and Materials Science, Maseno University, P.O. Box 333, Maseno 40105, Kenya

Address correspondence to Reccab M. Ochieng, reccabo@yahoo.com

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Abstract More often than not, the study of solar stills and their performance is restricted to the solar radiation at the place of study, certain parameters and factors have been found to improve the performance of solar stills in terms of efficiency. We investigated some of these factors namely: wind speed (v) and wind direction, angle of inclination (β), of the cover, ambient temperature (T_a) of the surrounding air, temperature (T_w) of the water, and the internal cover (T_c) temperature as well as the solar radiation and found out that their variations affect the efficiency of a single basin solar still considerably.

Keywords single basin solar stills; improved performance; efficiency; factors

1 Introduction

Solar still technology was first developed in 1872 by Carlos Wilson. In 1920, Kaush tried to improve the performance of the still by using metal concentrators to focus solar energy on brackish water. An efficiency of 50% was achieved, and these results were later confirmed by Pasteur in 1928 [20]. In 1930, Abbot applied the technology of focusing solar energy onto tubes containing polluted water by using cylindrical parabolic reflectors. The system worked with an efficiency of 80% [9]. Lof, in 1961, investigated the performance of single basin stills with respect to variations in solar radiation, ambient temperature, area of cover, wind velocity, and water depth [20] and his investigations revealed that productivity increased with increased solar radiation and that productivity also increased with increased ambient temperature. Increase in area of cover increased productivity as well. He also obtained high productivity with low wind velocity and noted that low water depths enhanced high productivity.

Direct variation between solar radiation and the performance of solar stills was later confirmed by Akinsete et al., in 1969 (Sodha et al. [20]). Similar results were obtained by

Zein et al. in 1986 (Alawi et al. [5]) who also confirmed Lof's results regarding the effect of ambient temperature on still's performance. However, Akinsete et al., in their research of 1969, proposed that the effect of energy losses from the still is less significant at higher ambient temperatures.

Morse and Read studied the effect of wind velocity on the still's performance in 1968 and found out that distillation rate does not depend on the velocity of wind [20]. Similar investigations were done by Cooper in 1969 and Coliman in 1972 and they too confirmed that there is no relationship between wind velocity and still's performance. It is worth noting that this result contradicts the one found by Lof in 1961.

Cooper (1969) studied the effect of water depth on productivity of solar stills and found out that productivity decreases with increased depth [7]. This is in agreement with Lof's results of 1961. However, there is no mention of optimum depths needed for the still to function most efficiently.

Bloemer investigated the effect of angle of inclination of the cover on still productivity in 1965 and found out that the still's performance was the same at inclinations of 10° and 45° [5]. Achilov (1972) did similar studies and found that maximum productivity occurs at an inclination of 30° [2]. However, Cooper in 1969 found that the cover's angle of inclination has no effect on still performance [20].

Later researches by Cooper and Read (1974) concluded that the minimum angle of inclination for the cover should be 10° [8]. They also found out, once more, that the angle of inclination has no significant effect on still's productivity.

Abdel-Salam et al. (1986) reported that productivity of stills is much higher at low angles of inclination and that it decreases with increasing inclination [1]. Their report also indicated that the effect of angle of inclination of the cover is more significant than the air volume covered inside and that for the same angle of inclination, stills with higher air

volume have lower productivities [5]. Once again, it is noted that there are contradictions on the relationship between productivity and the cover's angle of inclination.

In the recent past, new methods and techniques for studying solar stills for different applications have been developed and taken many different paths. Improvements on the new technologies have also taken form in the search of better performing solar stills. Eduardo et al. [11] developed a model for solar thermal symmetries in double solar stills in which the single and double slopes condensing covers and modeling equations describe a solution approach that considers the condenser as a single element. In the paper, a new lumped parameters mathematical model to study the asymmetries that arise in the temperature and distillate yield good results both experimentally and theoretically. Balladin et al. [6] evaluated the water quality produced by a concrete cascade solar still by comparison with the conventional electrically powered still used for the same purpose and the quality of tap water intake prior to the investigations. The tap water showed heavy metals, namely, sodium and calcium to be higher. Microbial assays showed that the cascaded solar still had highest colonies forming units of bacteria and other organisms (1400 CFU/mL) with respect to the electrically powered still (22 CFU/mL) and tap water (12 CFU/mL). These results present new ideas on the improvement of solar stills. Optimization of the tilt angle of solar collector as said before has been a major area of study in solar stills for many years. There is no doubt that there is need to for tilting to maximize performance of the system. Adnan et al. [3] employed a method based on annual solar fraction to study the performance and optimum inclination angles for a thermosyphon water heater. Using powerful computer program Transient System Simulation (TRNSYS), their results revealed marked variations on the optimum tilt angle for various locations in Jordan. However, Rahim [18] discusses a new method for storing excessive heat during day time for continuation of the process at night in solar stills. The technique divides the still into evaporating and heat storing zone and combines advantages of shallow and deep stills.

To improve efficiency, multiple solar stills have also been suggested by Fernandez and Chargoy [13], Le Goff et al. [16] whereas Lawrence and Tiwari [15] and Shariah [19], Potoglou et al. [17] present more work on evaluation, optimal design, and application of solar stills, respectively. It is on the basis of this introduction that this study was carried out.

2 Some background on solar stills

Distillation of water using solar energy has been practiced since 1872 in Las Salinas, Northern Chile where the oldest conventional single basin solar still was constructed [4, 10, 20, 21].

The technology has been used in Greece, Australia, India, China, Pakistan, Botswana and the Arab World. It is the oldest significant technological application of solar energy (Agarwal [4]) and many countries with abundant solar radiation are also adapting the technology to alleviate their water problems [14].

Different types of solar stills have been designed and further improvements have been done on the single basin still [10, 14, 20, 22]. Most common solar still designs consist of two main parts; black painted tray basin and transparent slanting plastic or glass cover. Brackish water is put in the basin and covered tightly. When the still is exposed to solar radiation, the energy passes through the cover and heat the water in the basin and the water vapor produced moves to the cooler underside of the cover where it is condensed. The condensate then flows down the underside of the slanting cover into troughs from which it is collected for immediate or later use.

Alternative designs of solar stills have been proposed and implemented. The operation of these designs is basically the same (Duffie and Beckman [10]) and can be categorized as deep or shallow basin stills.

Shallow basin stills have depths ranging from 1 cm to 2 cm and their constructions require highly skilled manpower. However, they are easy to operate and have low heat capacities which allow them to heat up very rapidly. They operate only during sunshine hours, but their productivity is much higher than deep basin stills [10].

Deep basin stills have minimum depths of 10 cm and require no external energy input other than solar energy. They retain energy for longer hours and can even produce distillates at zero insolation [22].

3 Single-basin solar still

Single basin solar still design consists of a black basin (tray) in which the brackish water is placed. The basin has a transparent cover that may be clear glass or hard plastic. There are various designs depending on the shape of the cover. The transparent covers can be slanting either upwards (Figure 1) or downwards (Figures 2 and 3).

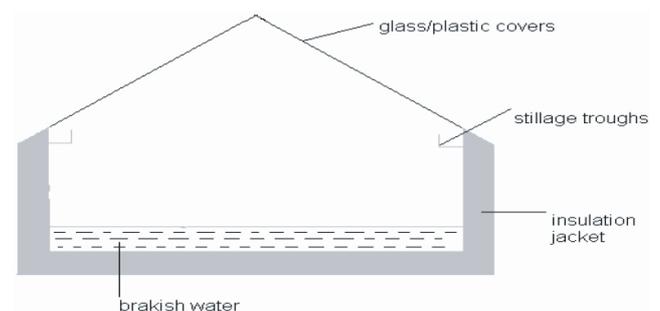


Figure 1: Single basin solar still (source: [10, 22]).

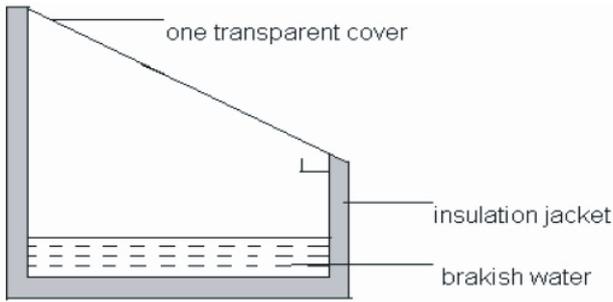


Figure 2: Single basin solar still (source: [20]).

Simple single basin solar stills are easy to construct and can have a lifetime of more than 20 years [12]. The design can be made portable or fixed at one place. In cases of large water masses, cascading the single basin still to form several stills is possible. These are called multiple basin stills [9].

4 Experimental

The equipment used during data collection was a basin type solar still held above ground level by a 0.762 m high wooden frame support. The still was assembled with the following components:

- (i) the basin,
- (ii) insulation jacket,
- (iii) condensate collection troughs,
- (iv) discharge and drainage pipes and tubes,
- (v) transparent glass covers.

A 1.6 mm (gauge 16) thick mild steel was used to make a basin of $610 \times 914 \times 76$ mm. The joints of the basin were completely arc welded to ensure no leakage occurred. A 13 mm hole was drilled at the bottom center of the basin to allow for discharge to take place during cleaning.

The insulation jacket of $762 \text{ mm} \times 1066 \text{ mm} \times 152 \text{ mm}$ was made from a $152 \text{ mm} \times 25 \text{ mm}$ piece of timber. Inside the framework was another of $610 \times 914 \times 152 \text{ mm}$ placed such that a gap of uniform width was left all round.

The space between the two structures was filled with wood shavings and saw dust as insulating materials. The bottom of the structure was also filled with the same material to a height of 73 mm from the external base and then covered with a 3 mm plywood. After nailing and welding these two structures firmly, wood glue mixed with sawdust was then applied to all joints and openings to make the system completely leak proof.

A 25 mm sheet was cut from the 16 gauge mild steel plate and bent into troughs which were arc welded all round the basin. This was done in such a way that at two diagonally opposite corners, the trough was 5.1 cm from the basin bottom and at the others, it was 3.8 cm from the bottom. One

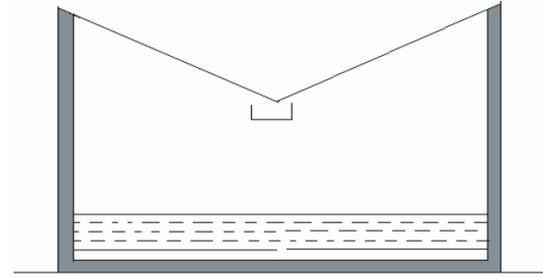


Figure 3: Single basin still with a downward slanting cover (source: [20]).

end of the trough was made lower than the other to allow for free flow of the condensate into the collection pipes. At the lower ends of the trough, a 10 mm hole was drilled and a 10 mm diameter copper pipe welded for collection of the distillate.

The 10 mm diameter copper collection or drainage pipe was then passed through another hole drilled through the basin just under the trough on the longer side of the basin. Once again, all the openings and joints were arc welded or gas welded to ensure that the system was leak proof.

A 10 mm hole was drilled on one of the shorter sides and a 10 mm diameter copper pipe welded into it. This acted as the feed point through which raw water was fed into the system.

Small pieces of iron rods of 5 mm diameter and 3 cm in length were welded horizontally at 2 cm points from the basin bottom. This ensured that the level of water was controlled and kept at 2 cm from the bottom before commencing data collection.

Thin sheets, 25 mm wide, were cut from the 16 gauge mild steel and bent at the center to form angle frames which were cut to the required dimensions and welded to the trough's periphery to serve as a bed for the roof and also provided the roof framework.

A 3 mm thick transparent piece of glass served as the cover of the system in which the shorter side of the cover was made upright, while the longer ones were made to slant. The highest slanting angle was 45° and was changed in subsequent structures to 30° and finally to 15° to the horizontal.

The basin and outside surface of the insulation jacket were painted black to ensure optimal solar radiation absorption.

Vapor pressures at the water surface and cover (P_{wb} and P_{wc} , resp.) were evaluated from the table of variation of properties of saturated water with temperature. To obtain the change in vapor pressure, Clapeyron-Clausius equation, given as follows:

$$\frac{dP}{P} = h_{fg} \frac{dT}{RT^2}, \quad (1)$$

was used in conjunction with the said table [23]. In this work, all measurements were taken during daytime at intervals of 15 minutes.

Several temperatures of the basin and cover were taken. From these measurements, average basin and cover temperatures were evaluated. Eleven Constantine-Copper junction thermocouples were used for measuring the temperatures of glass cover and T_c , water surface T_w , and the basin bottom T_b . The wires were connected to a programmed Data-Logger from which direct temperatures were read and recorded.

A wet dry bulb thermometer (Model BS 2842/66 from Casella Instrumentations Limited, London) was used for measuring the temperatures of the ambient T_a , and the external bottom of the basin T_{gr} .

A pyranometer (Model CM 5/6 Response Sensor, Serial Number 796521 from Crump Scientific Products) was used for recording the daily diffuse and direct solar radiation in Watts/m^2 . The instrument was connected to a digital millivoltmeter (multimeter from Fluke-Holland-BV, Tilburg), from which readings in millivolts were recorded. A conversion factor of 84.75 W/m^2 was used to evaluate radiation in W/m^2 . The values were integrated to get daily diffuse and direct solar radiation.

A Campbell Stokes Patterns (Model W 6030/A7861/1 from C. F. Casella and Co. Ltd) was used to record the number of direct sunshine radiation hours. Used with the instrument was a straight Casella London Card Number 6732. This card was burnt by solar energy focused by the Campbell Stokes Patterns. The period of burning reflected directly the number of hours direct sunshine had been received. The card was also used to align the Campbell Stokes Patterns in the East-West direction. This instrument is normally not accurate as the burn is not obvious in some cases. It does not respond to low radiation in the morning and late afternoon hours, and it is usually affected by humidity. From the experimental results, the minimum insolation required for the card to burn was found to be 540 W/m^2 .

An anemometer (Model WAA 12 serial number 37630 from Vaisalla, Helsinki, Finland) was used for recording the local average wind speed in m/s. This instrument, complete with speed and direction sensors, was connected to a display unit (WAD 21, Serial number 38696) from the same company. The unit indicated measurements of wind speed in m/s and direction in degrees from North.

Two graduated cylinders (of 10 cm^3 and 100 cm^3 capacities) served in measuring the stillage output in cm^3 , and a protractor was used for measuring the angles of inclination of the cover to the horizontal in degrees. Additionally, a digital watch (Casio) was used for recording the time intervals during which measurements were taken. The measurements

were taken at intervals of fifteen (15) minutes daily for periods 6 hours between 9.00 am in the morning to 3.00 pm in the evening.

The temperatures T_w and T_c were taken, and the corresponding values of h_{fg} were read from table AM 12. Substituting these values in equation derived from equation (1) as follows:

$$InP = \frac{h_{fg}}{R} \left(\frac{1}{T} \right) + 7.52 \quad (2)$$

gave the corresponding values of vapor pressures.

These were used to evaluate the convective heat transfer from the basin to the cover by applying the following heat transfer equations:

$$q_{r,b-c} = 0.9\sigma (T_b^4 - T_c^4), \quad (3)$$

$$q_{c,b-c} = h'_c (T_b - T_c), \quad (4)$$

$$q_e = 9.15 \times 10^{-7} h'_c (P_{wb} - P_{wc}) L_v, \quad (5)$$

as in Duffie and Beckman [10] quoted by Dunkle for the various internal heat transfer terms, where h'_c is the convective heat transfer coefficient given by

$$h'_c = 0.884[(T_b - T_c) + (P_{wb} - P_{wc}) / (2016 - P_{wb}) T_b]^{1/3}, \quad (6)$$

where P_{wb} and P_{wc} are vapor pressures of water at temperatures T_b and T_c , respectively, L_v is the latent heat of evaporation of water, and σ is Boltzmann's constant.

The efficiency of solar still is the ratio of the energy of productivity to the total incoming solar radiation and is expressed as follows:

$$\eta = \frac{q_e}{G}. \quad (7)$$

5 Results and discussion

The average efficiency of the still inclined at 30° to the horizontal when the collection tubes were closed was found to be 0.4278. When the tubes are opened to allow for free-flow, the efficiency increased to 0.4951. Therefore increase in efficiency is 0.0673 giving a 15.73% increase. Thus, for efficiency to be high, q_e in equation (7) must be as large as possible. This is evident from equations (3) and (4). Since P_{wb} and P_{wc} depend on temperatures T_b and T_c , good stills should be designed such that a large temperature difference $T_b - T_c$ is achieved.

The average rate of distillation when the tubes were closed for a 30° inclination was $63.82 \times 10^{-6} \text{ Kg/s}$ and was $73.31 \times 10^{-6} \text{ Kg/s}$ when free flow was allowed to take place which gives an increase of distillation rate of $11.49 \times 10^{-6} \text{ Kg/s}$ and translates to an 18% increase.

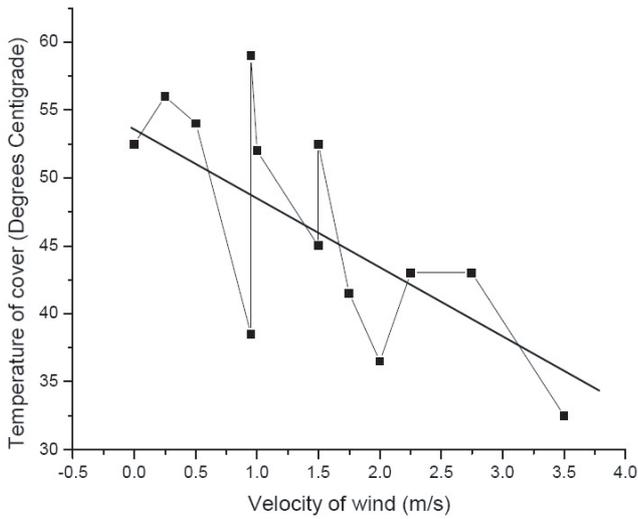


Figure 4: Temperature of cover versus wind velocity at inclination of 45°.

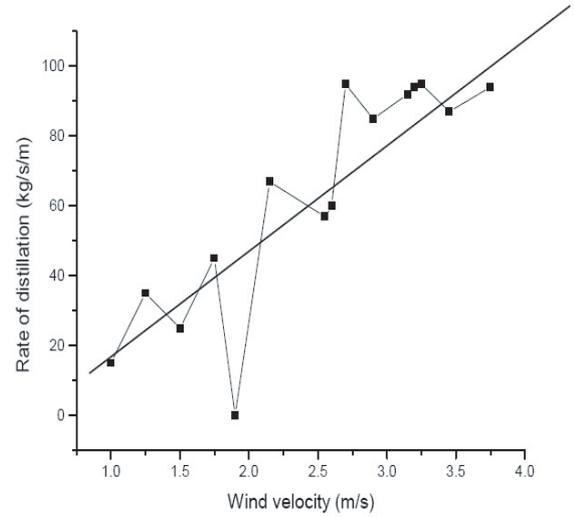


Figure 5: Graph of rate of distillation versus wind velocity at inclination of 15°.

It follows that a solar still performs better when the distillate is allowed to flow freely from the troughs into the collection points. Possible causes for this change in performance include pressure build-up in the still. During free flow, the pressure in the air jacket is low and this allows evaporation to take place faster thereby enhancing rate of condensation. When the tubes are closed, pressure build-up in the still inhibits evaporation from the basin, and the amount of distillate collected is subsequently low.

Another possible cause is that the initial absorption of solar radiation by the moisture particles accumulated in the still. This minimizes the amount of solar energy reaching the basin resulting in a lower rate of evaporation. In free flow, this effect is minimized, and the rate of evaporation is boosted by the high solar radiation levels reaching the basin bottom. When the collection tubes are corked, low solar energy is received at the bottom due to scattering by the cumulative moisture build-up in the still which has the effect of reducing the rate of heating on the water surface and, subsequently, rate of distillation.

The graph of wind velocity versus temperature of cover (Figure 4) show that the temperature of the cover decreases with increased wind speed. The ambient’s convective heat transfer coefficient depends directly on wind speed. It follows, therefore, that at high wind speed, the rate at which heat energy is transferred from the cover to ambient through convection is high. This results in a high rate of cooling on the cover.

Since high wind speeds result in high rates of cooling on the cover, it consequently follows that the rate of condensation on the cover is also increased at high wind speeds. Hence, the productivity of solar stills is directly proportional to the speed of wind. Figures 5, 6, and 7 illustrate this fact.

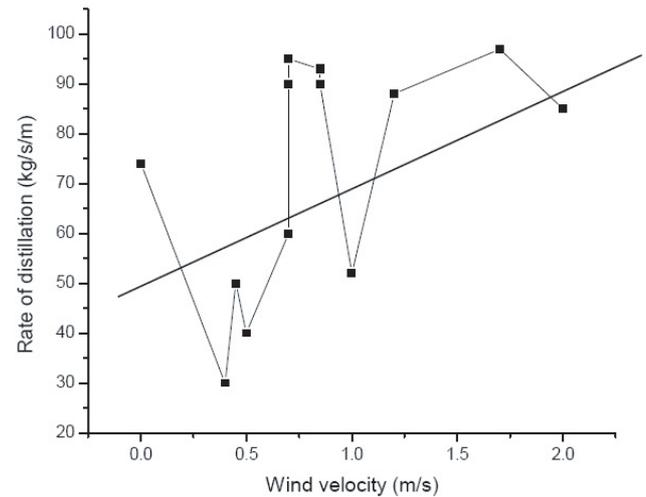


Figure 6: Graph of rate of distillation versus wind speed at inclination of 45°.

6 Conclusion

For a given angle of inclination, results indicate that the productivity of a solar still varies directly with solar insolation and that the productivity is proportional to the wind speed. These results validate earlier results by many workers that wind speed indeed affects the rate of distillation, thus the productivity of single basin solar still. Productivity increase with temperature difference between the cover and the basin still was also validated as the results showed and that the productivity is greater when the distillate is left to flow. When the angles were varied, results show that productivity is most steady at 15° of cover inclination at

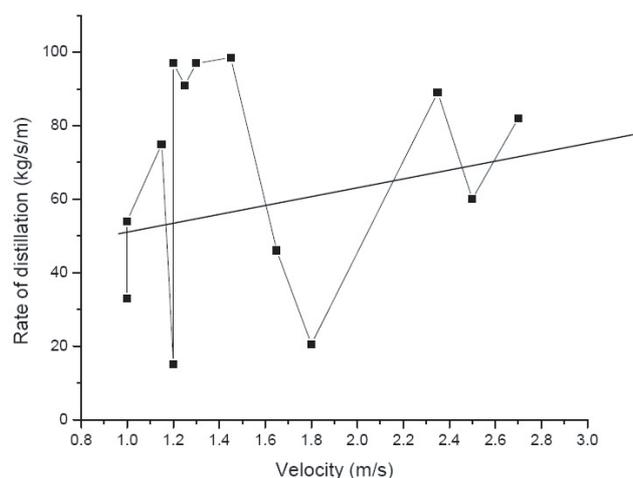


Figure 7: Graph of rate of distillation versus wind speed at inclination of 36° .

different weather conditions. The prototype was always able to produce over 1.2 liters of water under changing weather conditions. This confirms Abdel-Salam's theory that solar stills perform best when the covers are as close to the basin as possible.

It was further determined that the basin area required for a family of 8 people is 14.12 m^2 . This result gives a foundation for designing solar stills for specific requirements.

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