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The Effect of Cover Geometry on the Productivity of a Modified Solar Still Desalination Unit

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Abstract

Desalination methods based on renewable energy offer a promising solution to both water shortage and environmental degradation problems that continue to grow globally. The solar still is one such method that uses a sustainable energy source to produce potable water albeit at a relatively low productivity rate. A new modification has been introduced to the conventional solar still to enhance its productivity. The modification consists of a light weight, black finished, slowly-rotating drum, which leads 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. In this paper, three different cover geometries of the modified still are studied and the effect of cover design on the performance of the still in terms of measured temperatures and productivity is considered. The three cover designs are as follows: double-sloped or triangular, single-sloped and curved cover. In addition, a conventional double-sloped still without the rotating drum is operated in parallel as a control and the findings of this study are reported and discussed.

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Keywords: Cover geometry; rotating drum; temperature; solar still; water productivity

1. Introduction

The solar still is a simple and sustainable water production method that has been in operation for many years. Its main limitation, however, is the relatively low productivity compared to other desalination methods. This challenge has been the focus of intensive research with the objective of developing modified solar stills with higher productivities. A major concern while increasing productivity is nonetheless to maintain economic feasibility and

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Nomenclature

C	Curved solar still
S	Single-sloped solar still
T	Triangular solar still
T_g	Temperature of solar still cover
T_{g0}	Initial temperature of solar still cover
T_w	Temperature of water in the basin
T_{g0}	Initial temperature of solar still cover

simplicity in construction, maintenance and operation. Modified solar stills, which may include separate condensers, heat collectors, reflectors, sun-tracking devices and others often require extra space, are more complex and hence the increased productivity may not compensate for the additional entailed costs. On the other hand, a new simple modification has been introduced to the conventional solar still and has proven to significantly increase its productivity with minimal cost increases. A partly submerged slowly-rotating light-weight hollow drum is introduced within the still cavity. This allows the formation of thin water films that are continually collected from the still basin and that evaporate rapidly due to the high temperature of the drum. The energy required for the low rotational speed of the drum could be easily provided by a renewable source e.g. one solar panel is enough to operate the system. Compared to other studies where the enhancement in productivity is less than 100 % in most cases, often ranging between 30-40%, the new solar still with the drum yielded an average enhancement of 250%. Ease of operation and maintenance, low cost, and simplicity are therefore maintained while productivity is significantly increased. An important parameter affecting the performance of a solar still is its cover shape. In order to determine the effect of the cover geometry on the yield of the new developed system with the drum, different cover geometries were proposed, constructed and experimentally studied. These designs are as follows: (i) Triangular or double-sloped cover [T]; (ii) Curved cover [C]; and (iii) Single-sloped cover [S]. In addition, a base or control solar still [B] that has a double-sloped cover but does not include the rotating drum is studied in parallel for comparison.

A number of studies have examined the effect of cover geometry and inclination in solar stills with the purpose of optimizing the amount of solar radiation captured by the still [1-4]. Tripathi and Tiwari [5] reported that the change in length for a given height and width of a still does not affect the daily output but the change in the height of the north wall for a given height affects the daily output. Single sloped stills have been reported to give better yield in winter while double sloped stills performed better in the summer [6]. On the other hand, for locations with latitude higher than 20°, single-sloped stills are preferable whereas for lower latitudes, double-sloped stills facing north and south directions and having a cover inclination equal to the latitude angle could receive sun rays close to normal throughout the year [7]. A pyramid-shaped cover has also been used but did not improve the productivity [8]. Other researchers have utilized different cover concepts by changing the basic still configuration using vertical stills [9], spherical stills [10], tubular stills [11], multiple-stage stills [12-19], hemi-spherical stills [20], elliptical metallic stills [21] or transparent tubes as solar stills [22,23]. A critical review of these developments as well as of the effects of important parameters including the cover geometry on the performance of solar stills has been given in [24]. This paper reports on the effect of cover design and geometry on the performance of the new solar still system in terms of measured temperatures and water productivity.

2. Materials and methods

The experiments for this study were conducted at the American University of Beirut (AUB), Lebanon over a series of months between May and October. Four basins were constructed at the engineering workshops of AUB and three drums (0.6m diameter, 1.4 m length) were mounted into three of them, while the fourth still was used as a control i.e. with no drum. The water basins (0.67m x 1.5m, giving a unit squared meter of surface area) were constructed of plywood 18 mm thickness and coated with black fiberglass material to maximize solar heat absorption. Since annual yield of a solar still is reported to be at its maximum when the condensing cover inclination is equal to the latitude of the place [25], based on the location of this study, the slope inclination was chosen to be 23°. Aluminum channels for distilled water collection were used to collect the distillate. One Photovoltaic (PV) panel per system was sufficient to operate the motor for drum rotation on solar energy. Aluminum sheets mill finish 3000 x 1500 x 1.0 mm for the drums were wrapped to form the drums, which were then painted with mat black. Low-carbon steel shafts (20 mm diameter x 1.7 m length) were mounted on 20 mm ball-bearings and used to install the drums in the basins. The still covers were made of plexi-glass that was cut into the required dimensions and assembled. The stills were fed in batch mode via inlets that allow for basin filling. Outlets connected to the aluminum channels for distillate collection as well as at the bottom of the basin for brine discharge were also installed and controlled with ball-type valves. Thermocouples (Type K) were used to measure the temperature at four locations for each of the experimental stills as follows: inside and outside the still cover, inside the still cavity and within the water in the solar still basin. The thermocouples were attached to a board connected to a PC for continual reading of temperature. Digital scales (CPWplus) to measure the distillate water output were supplied by AdamEquipment (adamdu@adamequipment.com) and were equipped with a software that allows real-time reading of the collected weights. Distillate was collected in 6-liter pyrex Erlenmeyer flasks. Figure 1 shows the evaporation and condensation processes in two of the stills (single-sloped and curved covers with the rotating drum installed within the still cavity) as well as the control solar still (without the drum).

Fig. 1. The curved (top), single-sloped (bottom left) and control (bottom right) solar stills

3. Results and Discussion

3.1. Impact of geometry on still performance

Collected data throughout the experimental study showed a statistically significant improvement between the new setup and the control. Figure 2 shows the average cumulative volume in liters as it varies with time during typical days in August for each of the four systems. Similar results are also obtained for other months (data not shown). No particular cover gave the best performance in all cases and the results varied from month to month as the particular inclination of the cover and the location of the sun directly affected the amount of solar heat absorbed. For example, in the month of September, the average improvement varied from 141 to 145 to 166% for the curved, triangular and single-sloped systems relative to the control (p-value <0.05). In the month of May, the improvement reached 190% for the triangular system (p-value <0.05). It was found that for all conducted experiments, the solar stills with the introduced modification, i.e. the added drum, performed better than the control, which had no drum installed.

Moreover, the growth of algae and stagnation problems, which can reduce the heat transfer to the brine [26] were solved in the modified stills as the introduced drum constantly renewed the evaporating water film and ruptured the brine surface layer thereby preventing the shielding layer that normally develop in conventional stills.

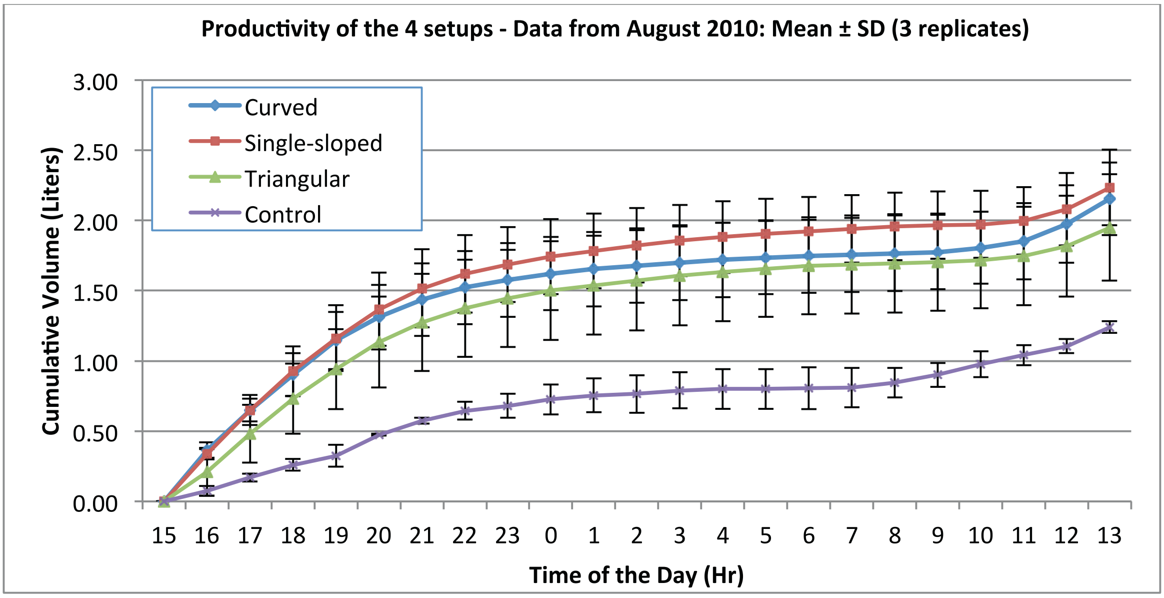

Fig. 2. Water productivity of the modified solar stills and the control still without the rotating drum

3.2. Impact of water temperature in the still on productivity

An analysis of the experimental data set for the measured temperatures of the brine water, air within the system and cover temperatures allowed the correlation of these temperatures with the still performance for the different cover geometries. Figure 3 shows the variation in the basin temperatures and in the cover temperature difference i.e. difference between inner and outer cover temperatures. Analysis of the temperature data allowed a better understanding of how the drum impacts the system and which among the different locations i.e. water, air within still cavity or cover, has the highest effect on the still productivity. The temperatures for the control still tended to be in the lowest to the low medium range in all cases and hence the advantage of the drum was evident in raising the temperatures within the still cavity as well as in the basin water. This increase in temperatures had a direct impact in improving the productivity of the still and it was examined which of the three temperatures i.e. water, system or difference in cover temperatures, contributed most to this enhancement. As an example, during the month of June, the curved still, which gave the highest yield among all stills, showed the lowest difference in cover temperature during off-shine hours whereas it's the highest in the morning. Moreover, the curved still shows the highest temperature for the still cavity and for the basin water. This direct correlation between temperatures and yield, however, was not general for all months. Table 1 summarizes the impact of each of the measured temperatures on productivity throughout the experimental period for the different cover designs. For the water temperature, during the 4 months period ranging from May to August, the temperature of the water in th basin was highest for the curved still (53-54°C), which showed the highest productivity during this period. As for the system temperature, the highest recorded temperature varied from month to month among the stills. In May, the highest system temperature was for the single-sloped still but this did not correspond with the still having the highest productivity.

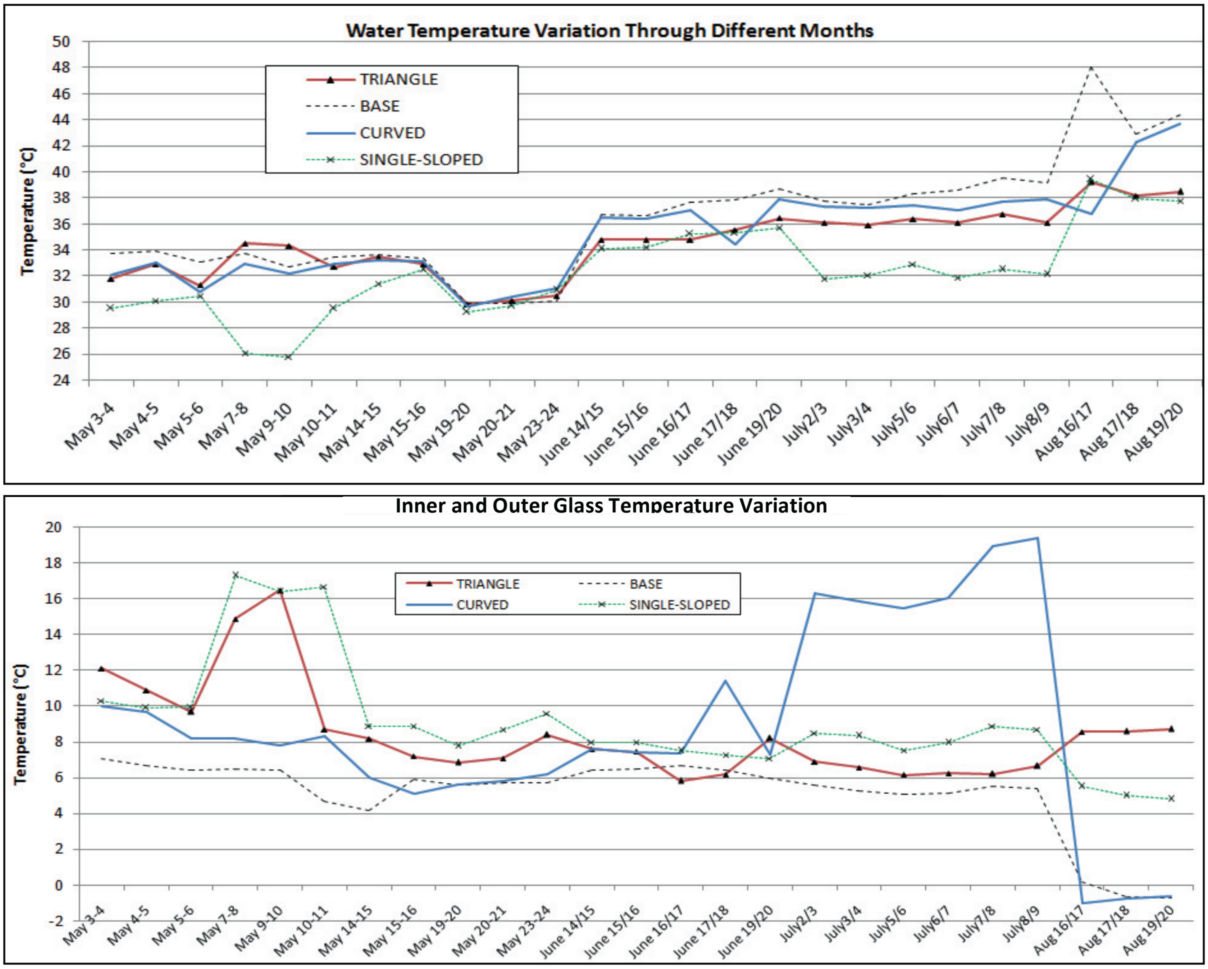

Fig. 3. Water temperature (top) and cover temperature difference (bottom) variation over the months for the four solar stills

Similarly, in August and September, the highest system temperature was for the triangular still, which did not show the highest productivity. In June, the system temperature was highest for the curved still followed by the triangular then the single-sloped still in the morning hours. In July, this trend also continued and became more pronounced whereby the temperature in the curved still was considerably higher than that in the triangular still, which was in turn significantly higher than that in the single-sloped still.

Table 1. Impact of temperatures on the water productivity of the stills (C: curved; S: single-sloped; T: triangular)

Month	Max. Temperature for Water in the Basin	Max. Temperature for Air in the Solar Still System Cavity	Max. Difference between Inner and Outer Cover Temperatures	Comparison of water productivity for the stills
May	53°C [C]	56°C [S]	17.5°C [S]	C >> T > S
June	54°C [C]	62°C [C]	36°C [C]	C > S ~ T
July	54°C [C]	62°C [C]	46°C [C]	C > T > S
August	54°C [C]	57°C [T]	19°C [T]	S > C > T
September	54°C [S]	51°C [T]	19°C [T]	S > T ~ C

A notable trend during the month of May was the highest temperature recorded for the single-sloped still in the morning. Starting from noon and through all off-shine hours, the triangular still had the highest temperature though the temperatures in the 3 stills had close values. By noting the system temperature effect on productivity, it can be deduced that the morning hours have the greatest contribution.

3.3. Statistical analysis of temperature data

Among all measured temperatures at the four different locations in the solar stills, the highest water temperature in the basin generally corresponded to a higher productivity. The temperature of the air in the still cavity apparently did not correlate with productivity as significantly as the water temperature since as can be observed from Table 1, systems having higher inside-air temperatures are not necessarily performing the best. Similarly, a higher difference between inside and outside cover temperatures did not correspond with a higher productivity. The relatively short distance between the major evaporating surface i.e. the drum and the condensing surface i.e. the still cover partly explains this result. Therefore, other factors related to the particular geometry of the system seemed to play more significant roles in terms of performance than those expected in conventional solar stills. In order to confirm these observations that are based on a preliminary analysis of temperature results, a statistical software (STATA) was used to determine the significance of the correlation between water temperature and the productivity of the studied systems. It was found that the water temperature significantly correlates with the productivity of the single-sloped, curved and control stills (R^2 = 0.7, 0.9 and 0.7, respectively) but not for the triangular still. Similar analysis for the effects of the system temperature interestingly showed even stronger correlations for the same stills (R^2 = 0.8, 0.94, 0.85 for the single-sloped, curved and control, respectively). The correlations between the difference in cover temperature and the still productivity, on the other hand, was relatively weak confirming the above observations.

3.4. Sensitivity analysis

Figure 4 shows the theoretical results, based on a simulation model of the system, for the effects of various important variables relating to the temperatures of the stills. A matlab program was developed in order to build this model and was used to develop important correlations by varying the values for the parameters of interest. These correlations are less obvious to note in the experimental data due to the difficulty of fixing all parameters and varying only the one of concern particularly those related to weather conditions such as solar radiation, humidity and ambient temperature. Using the theoretical model, on the other hand, different scenarios could be studied separately. For the outputs shown in Figure 4, the initial water level is taken to be 2.5 cm and the drum speed is 4 rpm except for Figure 4a, which plots the effect of varying the drum speed on cover temperature T_g. In Figure 4a, it can be noted that keeping all other parameters constant, while decreasing the drum speed results in a lower cover temperature. This is expected since a more rapid rotation of the drum, which is designed to maintain a high temperature and which is at a close distance to the still cover, causes its high temperature to raise the cover temperature by convection. Figure 4b shows the effect of water temperature T_w on productivity. A 20% increase (or decrease) in the water temperature accumulates to a 5% increase (or decrease) in the still yield over a period of 24 hours. A 20% increase (or decrease) in solar radiation also results in a 5% increase (or decrease) in the water temperature (Figure 4c). On the other hand, the initial cover temperature T_{g0} i.e. at the beginning of the experiment has a minimal effect on productivity (Figure 4d) but the variation of the cover temperature as time proceeds does impact the water productivity of the stills.

4. Conclusions

The results of this paper have focused on comparing different cover shapes of the enhanced solar still and the factors influencing temperature variation at different locations in the stills. Single-sloped, double-sloped and curved-cover systems were studied in addition to a control double-sloped still without the modification i.e. the drum:

- Among the measured temperatures at four different locations in the stills i.e. air in the still, water in the basin and inner and outer cover temperatures, in general the highest air in the system and water temperature in the basin corresponded to a higher productivity with very few exceptions.

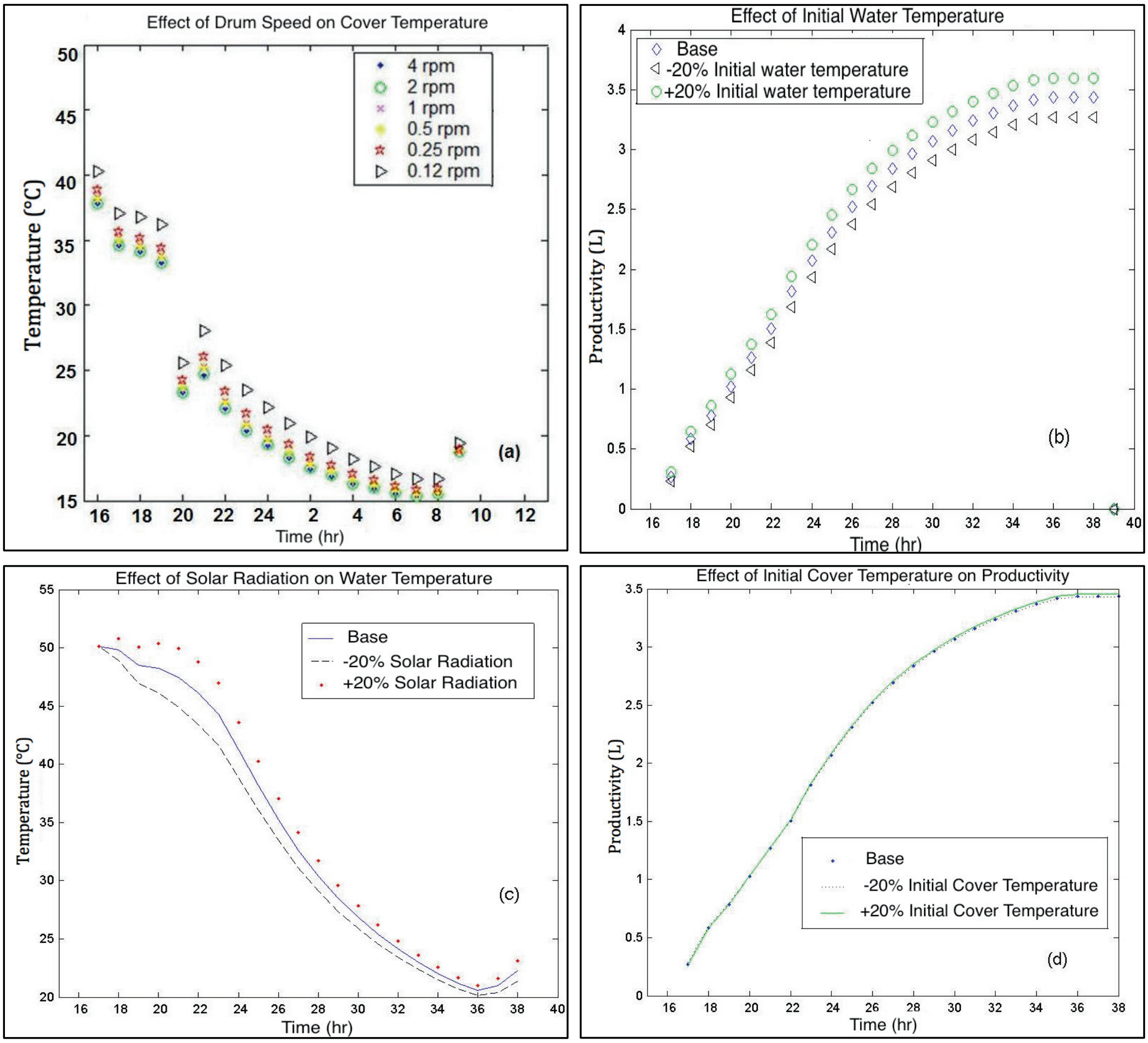

Fig. 4. Effects of (a) drum speed on cover temperature T_g, (b) solar radiation on water temperature T_w, (c) initial water temperature T_{w0} on water productivity of the solar stills, and (d) initial cover temperature T_{g0} on productivity

- 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. This was mainly due to the short distance between the high-temperature rotating drum and the still cover.
- 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%. For system temperature effects on productivity, it could be concluded that the morning hours have the greatest contribution. Since the drum overshadows the water surface, the water in the enhanced still basin acquires its temperature not from the direct rays of the sun as is the case with the conventional still but rather from the ambient conditions prevailing inside the still, with continuous mixing due to drum rotation that picks up

heat as it rotates. These conditions are hence impacted by interrelating parameters that may be operational, geometrical or related to weather conditions that are difficult to control and that require further studies.

- 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. Experimental studies of the proposed system over longer time periods can give insights on the reasons behind a best performing cover design for a specific month that was observed over the period of this study. Thermo-optical studies of the condensing covers and experimenting with other cover materials can also help in further improving the proposed design.

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