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Research article

Experimental study of the performance of hemispherical solar still with optimum value of rocks as heat transfer enhancers

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Abstract: Transformation of salty seawater into fresh water by the aid of solar energy is one of the solutions for overcoming the lack of these waters with an eco-friendly procedure. The use of solar stills is one of the solutions that use solar energy with a simple design to produce fresh water in small to moderate amounts. Hemispherical solar stills are one kind of still design that does not require a particle rotational orientation, and they have proved to be more efficient than traditional designs. Solar stills generally possess a low thermal efficiency, with limitations of working hours, i.e., only daytime. To overcome these problems, rocks placed in the saline water basin are used as heat storage materials to increase the working period of the design. In the present work, different amounts of river rocks are utilized to study the effect of this addition experimentally. Steady state tests are conducted to study the influence of these additive rocks on the enhancement of solar energy absorption, since increased working time is assured by published research. Two volumes of rocks (300 mL and 600 mL) were tested, and both increased water productivity, by 52% and 58%, respectively. The increases are explained by the increases in solar energy absorption, since steady state cases were used.

Keywords: solar still; hemispherical; productivity; heat storage materials

Nomenclature: A: Area, m^2; I: Solar irradiance, W/m^2; Pr: Productivity, kg/hr; R_a: Area ratio; R_o: Tray radius, m; R: Cover radius, m; $\boldsymbol{\eta}$: Thermal efficiency; θ: Angle of the tray sphere, $^{\circ}$; $\boldsymbol{\varphi}$: Azimuthal angle, $^{\circ}$.

1. Introduction

While fresh water resources steadily decrease in quantity and quality, new solutions have appeared. One of these solutions is the solar still [1], where saline and salty water are converted into potable water in small quantities by the aid of solar energy. According to some measurements, small or relatively high quantities of non-fresh water are subjected to direct and indirect sunlight while they are on a tray [2]. Water is vaporized from the tray, and the salt and salinity are left behind to fill the vacuum above it. Then, a moist air is created. The vacuum above the tray is closed by glass, with different shapes [3], which allows solar radiation to pass through it and provides a condensation surface. On this inner surface, the vapor condenses and loses its energy, since this heat is dissipated to the surroundings. Although this process is clean, eco-friendly and efficient, it is still slow, and hence some modifications are required [4]. To optimize the yield of fresh water and efficiency, many researchers have studied various design parameters [5,6]. Some of the studies have focused on using different shapes of glass covers [7]. The glass cover has a great importance in the desalination process since it has three functions: enclosing humid air, working as a condensation surface and heat transfer dissipation from the inside volume into the surrounding space by convection and radiation. Glass cover designs including pyramid [7,8], double glass [9], conical [10], tubular [11–13], spherical [14] and hemispherical [15–18] shapes have also been studied. In order to increase thermal efficiency of the solar still as well as increase the working hours after hours of sunshine, heat storage materials are used. Materials used to store heat include phase change materials [19,20] that can be placed under the tray surface, as well as other materials, such as rocks [21–25]. A hemispherical glass cover is one of the new designs used for stills, where a bigger surface area is provided compared to the traditional covers. In addition, orientation criteria are not required [25]. In the present work, a hemispherical solar still (HSS) was experimentally designed and fabricated in order to investigate the effect of the addition of river rocks on the steady productivity of the still. The addition of the rocks is intended to increase radiation absorptivity in addition to increasing working time as heat storage. Two volumes of rocks were tested and compared with the basic case of the solar still without rocks. The main objective was to determine the steady state productivity and thermal efficiency.

2. Internal surface area calculation

The internal surface of condensation has a great importance, since it is considered as a heat sink or heat dissipation surface for vapor to transform into liquid water. As this area increases, efficiency of condensation increases, because it has a direct relation with the values of inner condensation glass temperature. A cooler inner surface results in a higher condensation rate. Using a hemispherical dome is not just an advantage in terms of the orientation, as it also increases the relative area. Relative area (R_a) is the ratio between the inner condensation area and the evaporation surface area, which can be expressed by the following formula.

$$R_a = \frac{A_{condensation}}{A_{evaporation}} \tag{1}$$

A spherical surface dome cannot always be a perfect hemisphere, but it can also be a portion of sphere according to dimensions of both evaporation tray radius (assuming the evaporation tray as a circular tray) and dome radius. Figure 1 shows a tray of radius R_o covered by different spherical domes of different radii.

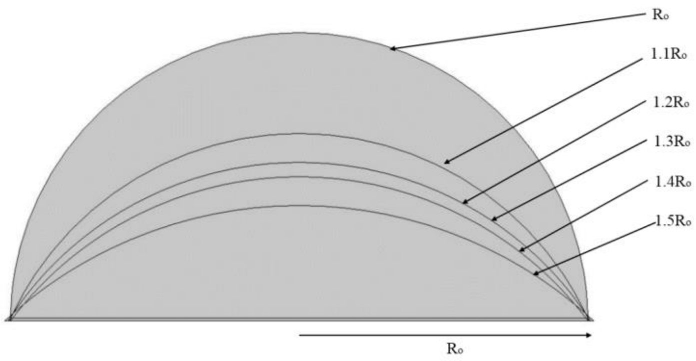

Figure 1. Circular tray covered by spherical domes of different radii.

The circular tray area can be obtained by calculating πR_O^2 where the inner surface area of portion of a sphere is found with radius (R) covering a circular tray with radius (R_o) into a portion of sphere up to an angle θ as shown in Figure 2 and as demonstrated in the following equation.

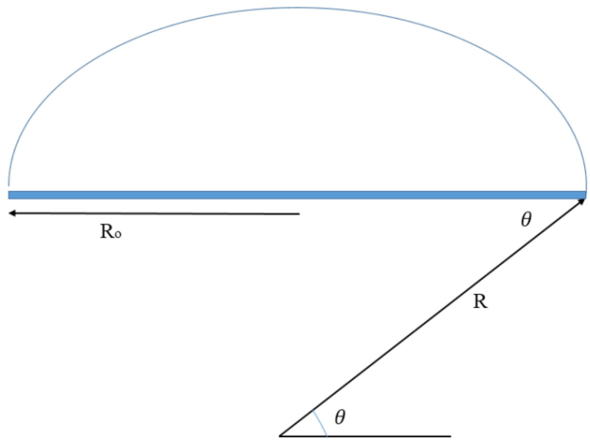

Figure 2. Representation of part of a sphere covering a circular tray.

$$R_a = \frac{\int_{\theta}^{\pi/2} 2\pi R^2 cos\varphi d\varphi}{\pi R_O^2} \quad (2)$$

where θ is the angle until which the sphere covers the tray and equals

$$\theta = cos^{-1}\frac{R_o}{R}. \quad (3)$$

By completing integration and substitution of (3), the following result was obtained by applying the following formula.

$$R_a = \frac{2R^2}{R_o^2}(1 - \sin\left(cos^{-1}\left(\frac{R_o}{R}\right)\right)) \quad (4)$$

Using a perfect hemisphere, Eq (4) shows the surface area is double that of the evaporation tray. Moreover, the sphere radius increases with approaching infinity while Ra approaches zero.

3. Experimental setup

A representative diagram of the setup used in the present work is shown in Figure 3. The experimental work setup consisted of two concentric trays with radii of 22.86 cm and 20.5 cm. The inner tray was used as a saline water container, which was painted black to increase solar radiation absorption.

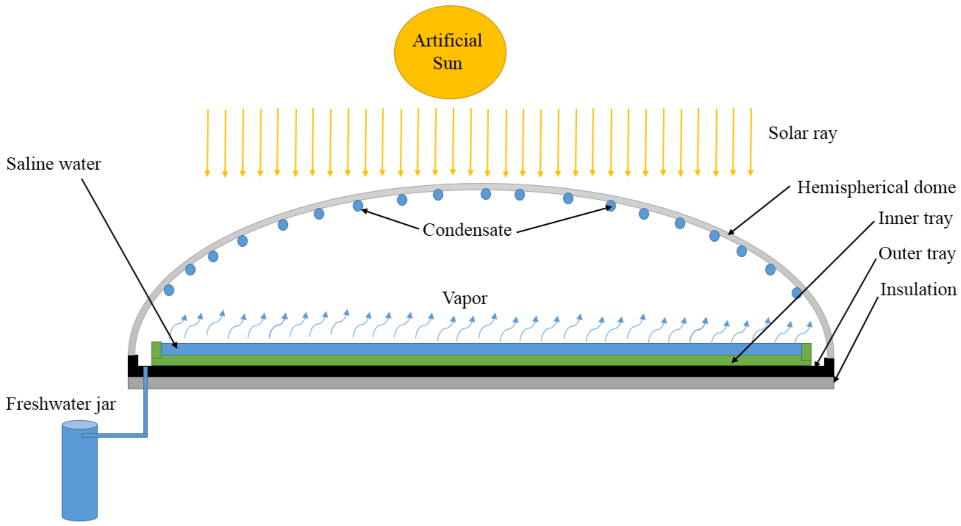

Figure 3. Sketch of present work experimental setup.

The inner tray was filled with water to a depth of 1.5 cm, as low depths have been shown to have maximum efficiency [26]. The outer tray works as a fresh condensate water collector, with an orifice on the side to drain water into the collection measuring jar. The drainage orifice is 5 mm in diameter, with a rubber pipe of the same size used to conduct drainage into the collection jar. Both trays were insulated on the bottom by a 4 cm layer of glass wool in order to reduce heat losses to the environment. The effect of glass wool compression was ignored since the whole device used was light, with shallow water storage. The outer tray was covered perfectly with a hemispherical dome of the same size in radius and 3 mm in thickness, as shown in Figure 4. The dome is made of clear plastic with a transparency of 0.9 and emissivity of 0.98. The surface of the dome was well treated to ensure dropwise condensation (which is confirmed to have a higher heat transfer coefficient [27]) on its surface.

Figure 4. Experimental setup used in the work.

In order to minimize leakage of water vapor from the enclosed volume, a foam tape was used between the glass cover and the tray. River rocks were used as heat storage materials, and two volumes were used: 300 mL and 600 mL. The rocks used are small in volume and dark grey in color, with semi-identical volumes for each one, as shown in Figure 5.

Figure 5. River rocks used in experiments.

Since the experimental work was conducted in tropical climate conditions, where it is cloudy most of the year, with partially sunny days, and since steady state behavior was looked for in the present work, experiments were conducted using an artificial sun. The artificial sun used here consisted of two 1000-watt halogen lamps placed over the still to simulate sun radiation.

4. Experimental procedures

In the experimental procedure, the saline water tray was filled with water to a depth of 1.5 cm, and then the inner and outer trays were covered by the hemispherical cover. The artificial sun then was turned on after completing adjustments for temperature measurements. Temperature measurements were done using K type thermocouples with the range of −50–150 ℃, as shown in Figure 6. Three points for every measurement location are implemented, for inner glass, outer glass, saline water, tray liner and atmospheric temperatures. Additional measurements were made for relative humidity, air speed velocity, productivity and solar radiation using proper tools, as shown in Figure 7.

Figure 6. K-type probes used to measure temperature.

Figure 7. Tools used for measuring air speed, solar radiation and productivity.

Measurements were delayed until all temperatures reached the steady state condition. Checking for no leakage was necessary to ensure accuracy of measurements, and after that, five readings, each after one hour, were taken for each case: no rocks added, 300 mL of river rocks added, and 600 mL of river rocks added. When all measurements are completed, artificial sun is shut down and waiting for another reading to measure productivity by the heat stored by the rocks.

5. Uncertainty analysis

In order to build confidence in the results obtained by the present experiment, uncertainty analysis was done. Normally, uncertainty has origins associated with the measuring process, namely, systematic and random, and it is estimated using the method proposed by Wheeler et al. [28]. In this method, dealing with the variables is dependent on other measured variables, like thermal efficiency in the present work, as in the following equation:

$$Error_{\eta} = \sqrt{\left(\frac{\partial \eta}{\partial I} Error_{I}\right)^{2} + \left(\frac{\partial \eta}{\partial Pr} Error_{Pr}\right)^{2}} \quad (5)$$

where $Error_I$ and $Error_{Pr}$ are errors associated with solar irradiance and productivity value, respectively.

6. Condensation process

Since producing fresh water by solar stills is sensitive to many variables, these variables are very difficult to control. Also, the variables are measured and marked for each explanation. Dropwise condensation, as expected, was present on the inner surface of the glass cover, as shown in Figure 8.

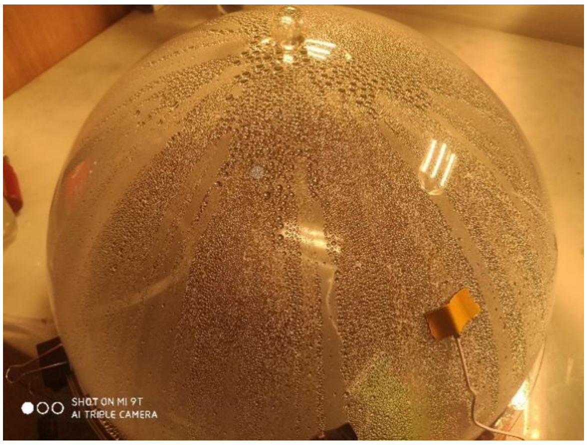

Figure 8. Dropwise condensation formed on inner surface.

Droplets are shown to have sizes ranging from infinitesimal to 4 mm in radius, for the largest droplets. Big Droplets are concentrated in the area near to the top of glass cover while the small droplets are concentrated in the area near the lower areas. To begin with, infinitesimal droplets are formed over the whole surface. In addition, droplets start to integrate with nearby droplets to create bigger droplets. Droplets that continue to enlarge, until surface tension forces are no longer able to sustain their weight, start to slide down and sweep all droplets in their way. This sweeping behavior explains the disappearance of very big droplets in the areas near the glass cover base.

7. Results and discussion

In order to understand the steady state behavior of adding rocks into the tray of saline water in the solar still, three sets of experiments were conducted: 300 mL of rocks, 600 mL of rocks and a control case for validation. In each case, five experiments were tested within an interval of hour for each. No measurements will be recorded until reaching the steady state case, where all temperatures should be constant. There still could be variations in values from set to set. Figures 9 and 10 show values of ambient temperatures and ambient air velocities during the experiments. These values are considered as inputs to the still for working, in addition to solar irradiance (in the following work, it varies slightly from 1100 to 1200 W/m^2).

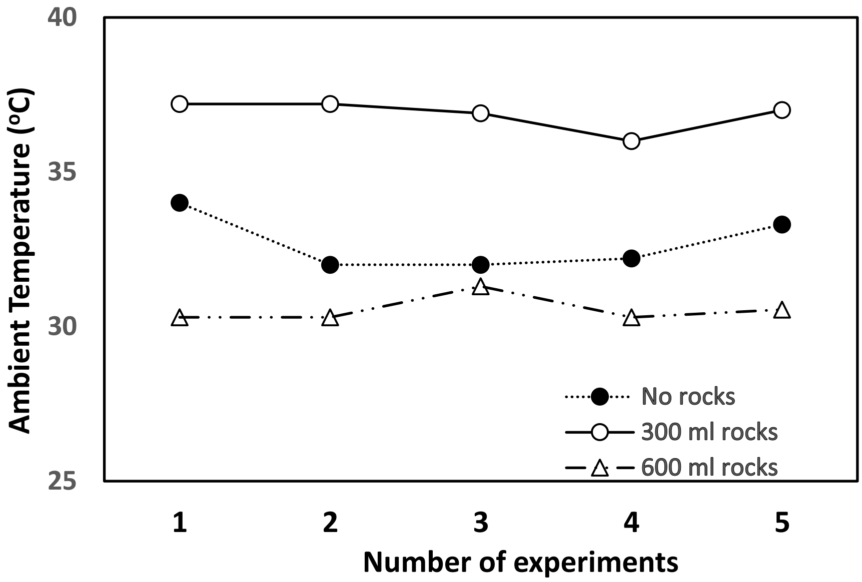

Figure 9. Ambient temperatures during experiments.

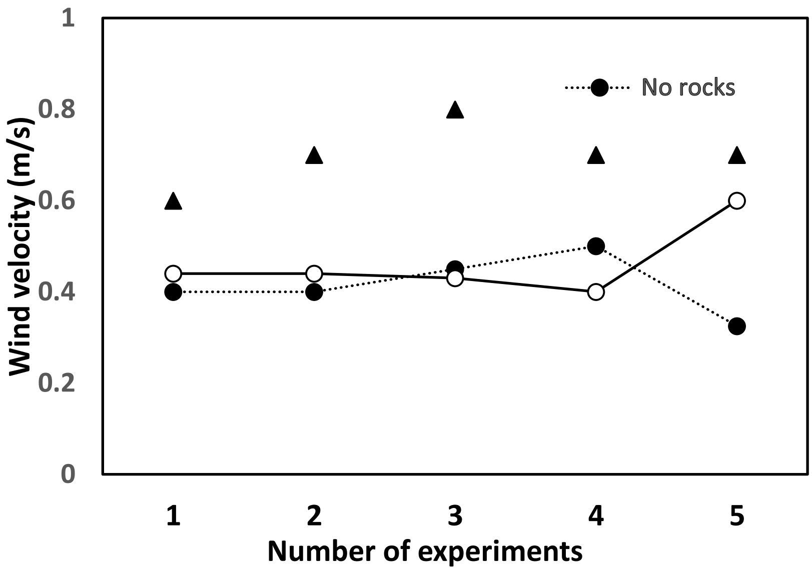

Figure 10. Ambient air velocities during experiments.

According to previous inputs, the results were started with temperature values of components. Basin liner, saline water, inside glass and outside glass temperatures are presented in Figures 11–14. It is obvious that the values in the no-rocks case are lower than those of the other cases, while the case of 600 mL has the highest value. Fluctuations may be present in the results due to inputs' fluctuations. However, the trend is clear in indicating the highest and lowest values. This behavior may be associated with enhancement in radiation absorption ability since these results are steady state. There is no other explanation for these increases since storage ability can only appear at the end of experimental operation, where storage ability appears after turning off the artificial sun. Basin liner temperatures are the most important results, since all other values follow their values.

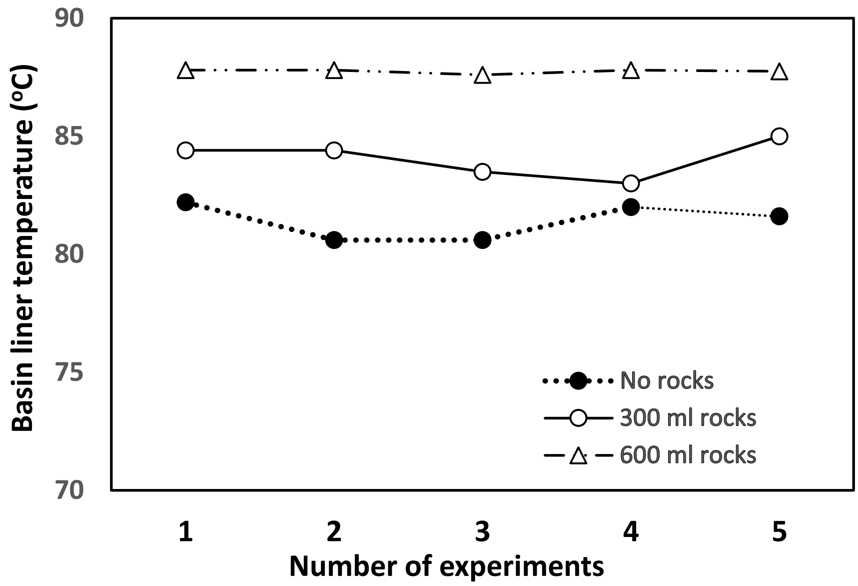

Figure 11. Basin liner temperatures in present study cases.

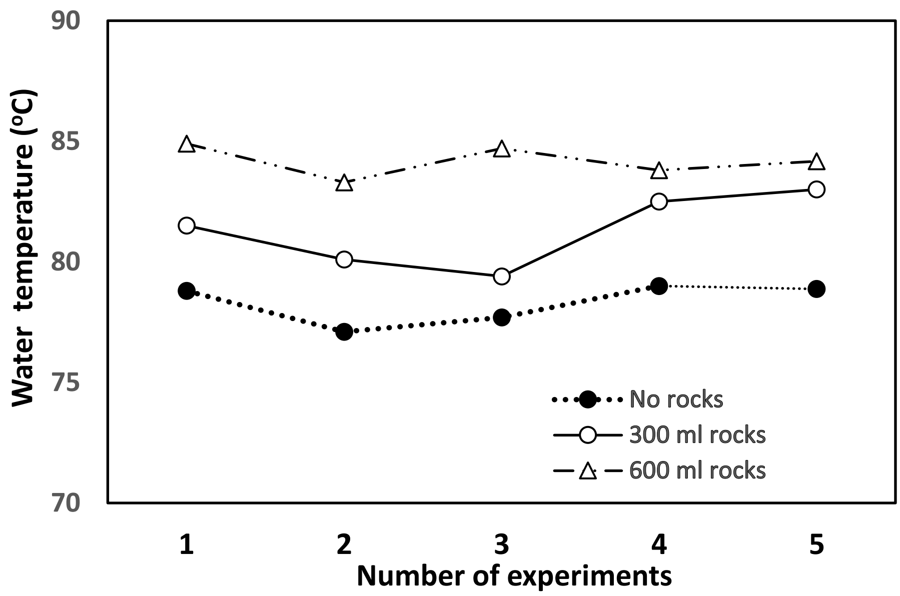

Figure 12. Saline water temperatures in present study cases.

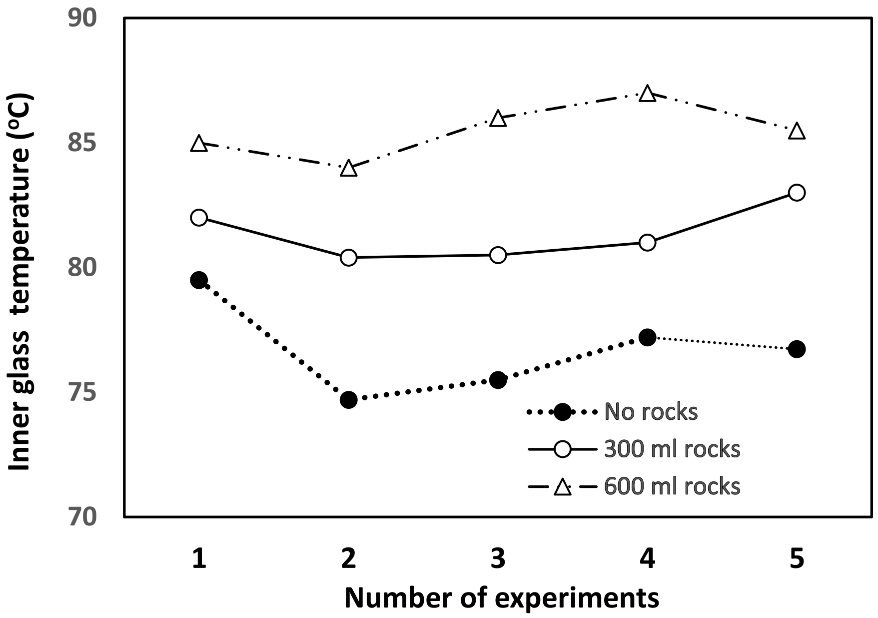

Figure 13. Inner glass temperatures in present study cases.

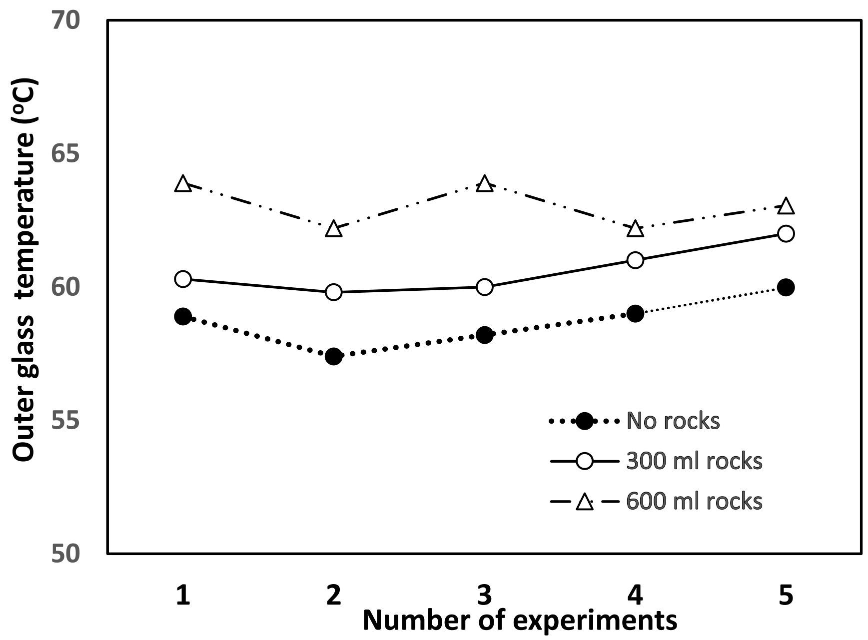

Figure 14. Outer glass temperatures in present study cases.

Figure 15 shows productivity values for the present work's cases. The HSS produced 1.05 L/m^2.hr, while the addition of 300 mL of rocks resulted in 1.6 L/m^2.hr, and the addition of 600 mL resulted in 1.67 L/m^2.hr. This means that the yield increased by 52% in for the 300 mL case and 58.7% for the 600 mL case. Therefore, adding rocks to saline water causes an increase in productivity values due to the increase in solar absorption, as mentioned before. The other reason that may be considered is the decrease of saline water volume due to maintaining the same water height after the rocks' addition. That means that there was a lower mass of saline water to evaporate than in the normal case. Therefore, the result may explain why the 600 mL case has higher productivity than the 300 mL case.

After turning off the artificial sun, another 1.63 L accumulated due to heat stored in the water mass and can be added to the total productivity, compared to 2.2 L and 2.6 L accumulated for the cases of 300 mL and 600 mL, respectively. These results were taken in a period of 8–10 hrs after finishing experiments to express total energy stored in the system. Certainly, the 600 mL case had the highest value of stored energy, since the greatest mass of rocks was used.

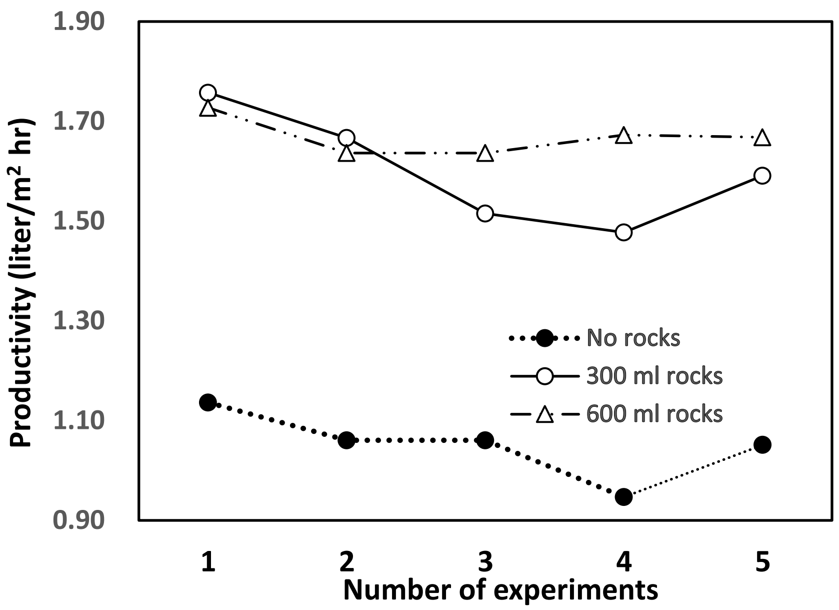

Figure 15. Productivities for cases of the present study.

Thermal efficiency, as shown in Figure 16, varied from an average of 20% for the normal case to 30% and 32% for the cases of 300 mL and 600 mL of rocks, respectively. These values are relatively low due to low ambient air speeds, which reduce heat dissipation to the surroundings. Reduction in heat dissipation causes more heat to be stored on the glass cover, which decreases productivity due to the increase in glass cover temperature.

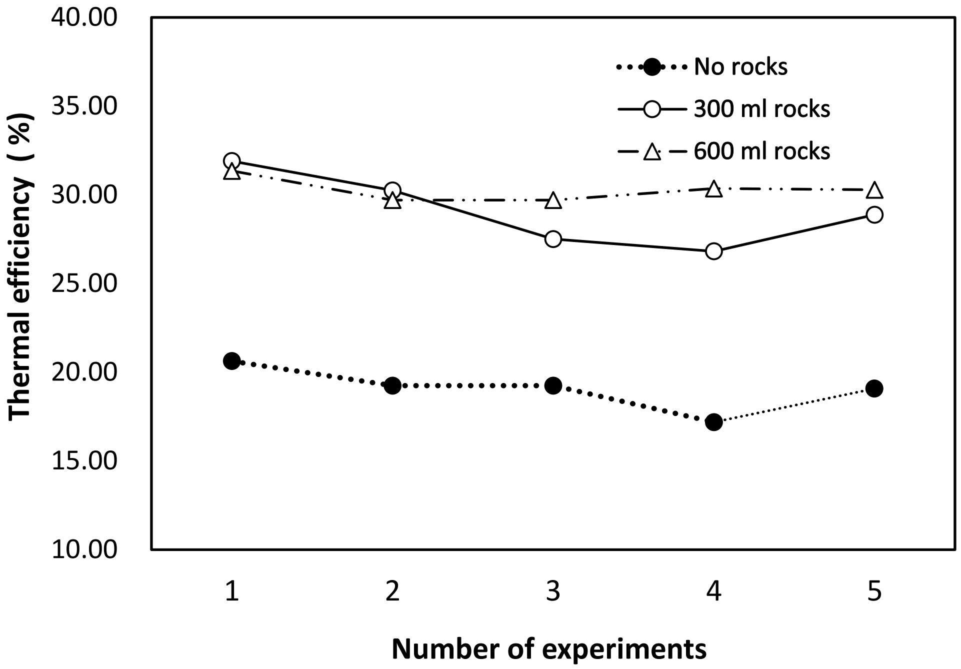

Figure 16. Thermal efficiencies of cases in the present work.

8. Cost estimation

It is important to estimate the cost for such stills. Fabrication and collecting costs of the present still are shown in Table 1. The most expensive part is the acrylic hemispherical cover, which is hard to find since it is not a commonly available object. Cost analysis shows that for the present area of 0.13 m^2, based on the saline water tray area, the cost is about \$61, while for 1 m^2 it is about \$205. These costs are relatively moderate values.

Table 1. Cost estimation for present still.

Component	Price ($)
Acrylic dome	40
Inner tray	5
Outer tray	6
Piping and fitting	10
Total for 0.13 m^2	61
Total for 1 m^2	205

9. Conclusions

A hemispherical solar still was fabricated and tested in the present work under steady state conditions using an artificial sun under controlled conditions. Two cases with rocks were examined, with additions of 300 mL and 600 mL to the saline water tray. The following observations were made.

- The HSS does not need any orientation since orientation is one of the biggest problems for traditional solar stills.
- The HSS has a bigger condensation area compared to a traditional still.
- The addition of rocks caused an increase in solar radiation absorption, shown as an increase in water liner temperature.
- Rocks also work as a heat storage material to increase the working hours of stills after losing sunlight.
- Increasing the rocks' amounts causes increases in solar absorption and heat storage capacity.
- A productivity of 1.06 L/m^2.hr was obtained for the traditional HSS, while the addition of 300 mL of rocks increased productivity by 52%, and 600 mL caused an increase of 58.7%.

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Conflict of interest

The authors have no conflict of interest.

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