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Performance evaluation of spherical and pyramid solar stills with chamber stepwise basin

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ABSTRACT

In this work, novel designs of single slope solar still are suggested. Spherical and pyramid shapes with chamber stepwise basin were added to the conventional solar still design. An experimental study was performed to investigate the effect of introduced design modifications on the output parameters of the modified solar still. The addition of semi-spherical and chamber stepwise design enhanced the productivity of modified distiller by up to 57.1% as compared with pyramid solar still.

Keywords: Solar still; Spherical shape; Pyramid shape; Chamber stepwise basin

1. Introduction

The supply of pure and clean water is a basic necessity for humans and animals besides food and air. Clean water is a precious source, which is becoming rare in many regions of the world. Solar stills have been used in the past to get salt from saline water. Nowadays, solar stills are used to purify saline water. Solar water distillation can be considered as one of the most important methods of using solar energy for purifying saline and brackish water. Single slope still is one of the cheapest solutions for purifying saline water which is suitable for different countries because of its simplicity of construction, low-cost, and ease of maintenance [1]. Intensive reviews on the use of different types of distillers and solar collectors are reported in Arunkumar et al. [2], Kalogirou [3], Badran and Al-Tahaineh [4], Al-Hayeka and Badran [5], Joseph et al. [6], Tanaka and Nakatake [7]. The effect of using different absorbing materials in solar distillers to improve the productivity of pure water is given in Akash et al. [8], Akash et al. [9], Nijmeh et al. [10]. Mathematical modeling of solar stills was introduced by different works, such as Tiwari [11], Tiwari et al. [12], Tripathi and Tiwari [13] Yadav and Yadav [14], Nafey et al. [15]. In these works, the heat transfer analysis and energy balance analysis are presented. Badran and Abu-Khader [16] conducted an experimental study on single slope solar still under Jordanian climatic conditions and then presented a detailed theoretical heat transfer analysis. Previous work introduced design modifications to the conventional solar still, involving the installation of reflecting mirrors on all interior sides, replacing the flat basin with a stepwise basin, and coupling the tracking system [17]. The addition of internal mirrors improved the still productivity up to 30%, while the stepwise design of the basin improved the thermal performance up to 180% and the coupling of the stepwise basin with a single-axis sun-tracking system enhanced the performance up to 380%. Another research conducted experimental work to study the effect of single-axis sun-tracking system on the performance of single slope solar still [18]. The comparison between the fixed and sun tracked solar still showed that the sun tracking system increased productivity up to 22%. Tarawneh [19] studied the effect of water depth in the basin on water productivity. The obtained results

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showed that the decreased water depth has a significant effect on the increased water productivity. The effect of water mass on the performance of triangular pyramid solar still with or without latent heat energy storage was studied in Sathyamurthy et al. [20]. They found that there is an increase of about 35% in the production of freshwater with latent heat energy storage than in the case of a solar still without it. Additionally, it was found that during the off shine period, the freshwater produced from the still is higher compared to the higher water mass.

A modification of a stopped solar still with water circulation using a feeding water tank filled with salted water and seawater was suggested in El-Agouz [21]. The results of the experimentation show that the performance of the modified stepwise still is higher than that of conventional one up to 43% and 48% for seawater and salted water with black absorber respectively, 47% and 53% for salted water and seawater with cotton, respectively. A vacuum distillation system for the purification of well water and desalination of seawater was proposed by Jitsuno and Hamabe [22]. The suggested system can produce salt as well as pure water. The thermal efficiency of this distiller is 70% and it can produce 10 kg/m^2 of pure water per day. Abdallah [23] introduced PV generator-powered electrical heater and chamber stepwise basin to the conventional single slope solar still. It was found that the added design modifications improved the productivity of solar still by up to 1,098%.

The main problem of a conventional still is that the productivity per unit area of this type of desalination systems is still relatively low. Therefore, there is a strong need to enhance the efficiency of traditional single slope solar still.

2. Spherical and pyramid solar stills with chamber stepwise basin design

In this section, two design modifications of traditional single slope solar still will be suggested. One of them involved the changing of shape to the pyramid type, and the other one involved the changing of shape to the spherical type.

2.1. Modified solar still design with a pyramid shape

The suggested solar still has a pyramid shape, and three collecting sides exposed to solar radiation. Also, this design has stepwise chambers, as shown in Fig. 1. The glass cover is added to each side, where, one side faces the sun at sunrise time, the second side faces the sun at solar noontime, and the third one faces the sun at sunset time. The second face is directed to the south.

The inside basin is divided into five step-wise chambers. Each step has a square shape. The biggest is 60 cm by 60 cm and the smallest is 20 cm by 20 cm.

The height of still is 71.6 cm and its width is 74 cm. The inclination angle of the glass cover is 44°. Steel thickness is 1.8 mm for chamber manufacturing and 3 mm for boundary manufacturing. The thickness of the glass cover is 6 mm. The still is painted black. The still is covered by a wooden box from the bottom and backside, leaving a distance of 20 mm between the metal sheet and wood. To reduce the heat losses, the gap between wood and metal sheet is filled with foam. The dimensions of the main body of the still are shown in Fig. 2.

When solar radiation starts falling through the glass cover into stepwise chambers filled with saline water, the kinetic energy of water drops increases. Water evaporates and condensates on the inner side of the glass cover. Condensed water on the glass coverslips due to gravity, down to the collecting tank. The pyramid still after manufacturing is shown in Fig. 3.

2.2. Modified solar still design with a semi-spherical shape

The suggested solar still has a semi-spherical shape. It is actually one quadrant of the sphere, as shown in Fig. 4. The chambers are designed to be perpendicular to solar radiation all the time from sunrise to sunset. The basin of this type has a chamber stepwise design, where the basin is divided into 5 stepwise chambers. Each chamber has a circular shape.

The dimensions of the chambers are shown in Fig. 5. The height of still is 60 cm, and the radius of the mechanical base is 70 cm and, the inclination of the glass cover is 28°. Fig. 6 shows the mechanical base for a glass cover, where the mechanical base is divided into 6 triangles with seven 12 mm × 3 mm steel rods. The thickness of the glass cover is 6 mm. The metal sheets are painted black to minimize the heat losses. The bottom side and backside still are insulated. A distance of 20 mm is left between wood and metal sheet, which is filled by foam.

The spherical basin design keeps the beam radiation more perpendicular to the basin metal sheet surface. For example, at the sunrise time and sunset time the beam radiation will be parallel to the basin of a conventional solar still, so, the metal sheet surface will not receive beam radiation. In the case of the spherical solar still, at the sunrise time and sunset time the beam radiation will

Fig. 1. Three-dimensional view of the pyramid still with chamber step-wise design.

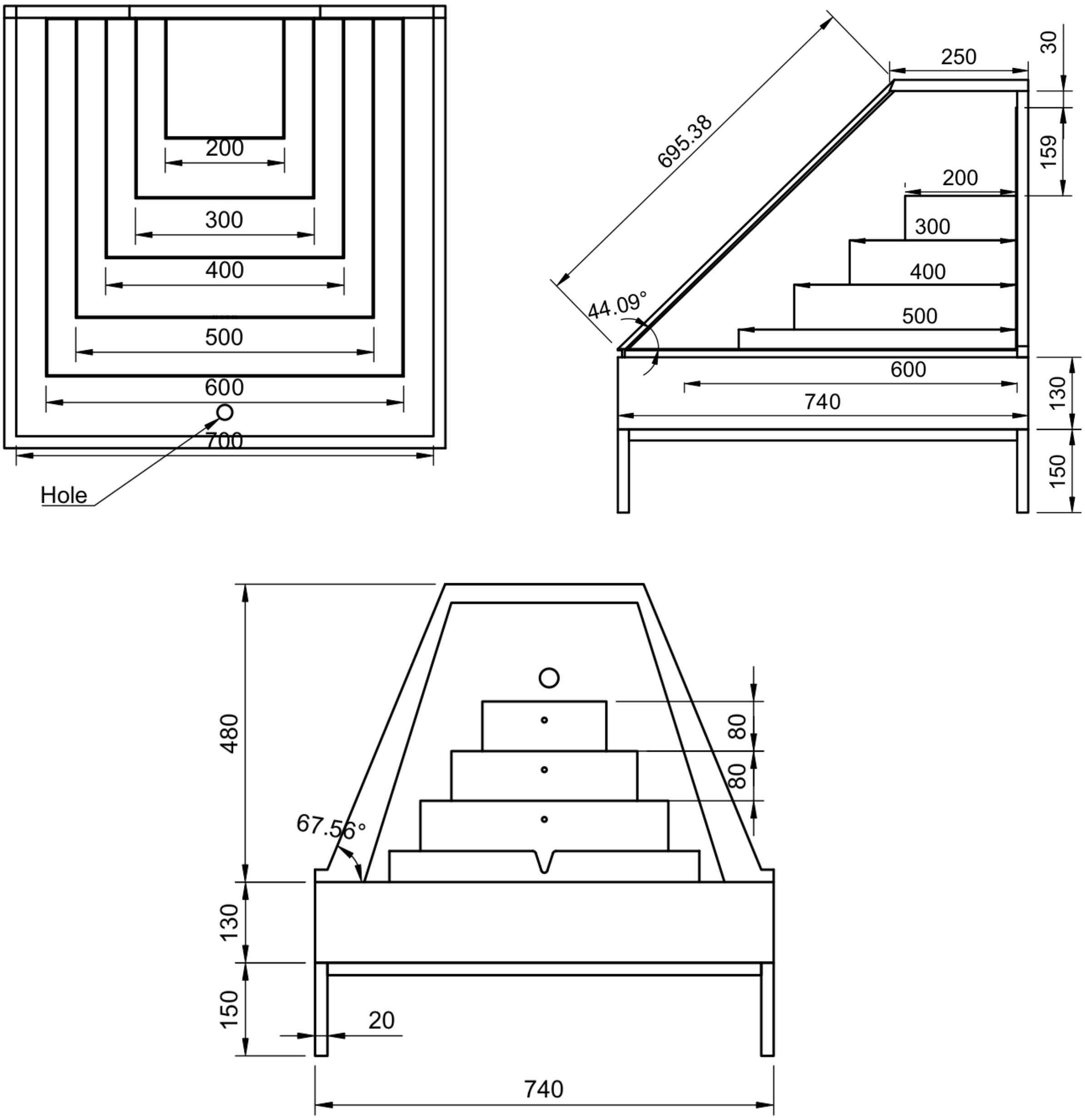

Fig. 2. Different views of the pyramid still with chamber stepwise design.

be perpendicular to the basin from the east and west sides. In pyramid shape, one side faces the sun at the sunrise time but with an angle of incidence not equals to zero. The second side faces the sun at solar noontime but with an angle of incidence not equals to zero. The third one faces the sun at sunset time but with an angle of incidence not equals to zero.

The solar radiation breaks through the glass cover into the semi-spherical step-wise basin which is filled with saline water. Water evaporates and starts condensation on the inner surface of the glass cover. The drops of water accumulate and slip due to gravity on the inner side of the glass cover, where it will be collected in an inclined path on its way to the collection tank.

3. Experimental procedure

The experiments were conducted on both stills, pyramid and spherical, under the same climate conditions. The experiments were performed at the same location in the Renewable Energy Laboratory in the Applied Science Private University in Amman, the Capital of Jordan. The experiments were carried out in winter on two different days (7th and 11th/1/2020) throughout the period from 7 AM to 4:30 PM. The readings of ambient temperature, solar radiation, inside water temperature in each still, as well as collected distilled water in each still had been taken in a 60 min time interval for the above mentioned days.

Fig. 3. The pyramid still after manufacturing.

Fig. 4. Three-dimensional view of spherical still with chamber stepwise design.

The electronic parts had been tested and calibrated before used in the various designs of the solar stills. The global solar radiation on a horizontal surface was measured using Kipp and Zonen pyranometer with a sensitivity of 15.53 μV/W/m^2. Calibrated thermocouples type–K coupled to digital thermometer was used to measure the temperature inside basins. The thermocouples were of Testo 110 type with an accuracy of 0.2°C for a temperature range from –25°C to 75°C.

4. Results and discussions

The readings for the first day (7/1/2020) are represented in curves. Figs. 7 and 8 show the solar radiation as a function of time and the ambient temperature function of time, respectively.

The temperature inside the basin for both the pyramid and spherical stills is shown in Fig. 9. The amount of collected distilled water for pyramid and spherical stills is shown in Fig. 10.

The readings from the second day 11/1/2020 are very similar to the readings of the first day. It is seen from the curves of inside water temperature for both stills that the maximum value is attained around 3 PM. The curves also show that the collection of distilled water accumulates from the early morning until the end of the day. The total collected water in the period from 7 AM to 4:30 PM for the first day was 1.275 L/m^2/d from the pyramid still and 1.678 L/m^2/d from the spherical still. The total collected water for the same time period for the second day was 0.875 L/m^2/d from the pyramid still and 1.375 L/m^2/d from the spherical still. Where the total basin area for spherical and pyramid stills equal 0.31 and 0.2 m^2 respectively. Table 1 shows production gains for different days. It is important to notice that the nighttime production of pure water is taken into account. For example, night time collection of the pyramid still is 250 mL/m^2, and for semi-spherical still is 677 mL/m^2 for the first day which is 7/1/2020.

The high productivity of spherical solar still can be explained by many factors such as:

- The spherical design of solar distiller makes the incident radiation more perpendicular to the metal sheet and water surface from sunset to sunrise which enables this type to collect more solar radiation.
- The gap between the glass cover and the water surface is smaller in the spherical design than the pyramid design. Consequently, the energy required to raise the vapor up is lower and the required time to complete this evaporation and condensation process is shorter.

The spherical still gave a higher production rate for the first day reaching 31.6% and for the second day reaching 57.1%. The effect of the spherical shape with the chamber step-wise design over the pyramid shape with three faces and chamber step-wise design is clear. On the other hand, it was found that the pyramid still with a stepwise chamber has improved productivity of distilled water up to 85% as compared to the traditional distiller [24]. The solar still with spherical shape and chamber step-wise basin has shown 57.1% higher productivity results than those of the pyramid still with chamber stepwise basin. That means the semi-spherical solar still and chamber stepwise basin can

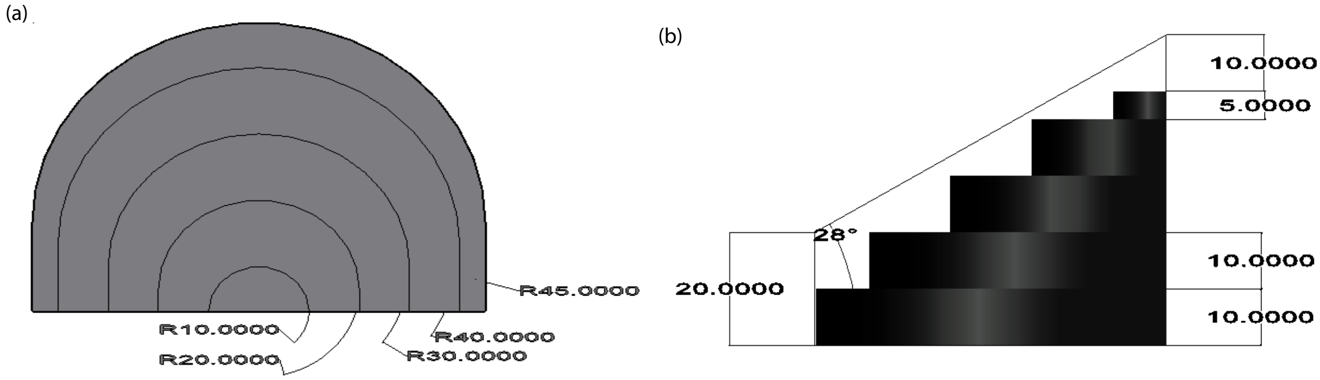

Fig. 5. Dimensions of spherical still with chamber stepwise design in cm: (a) top view and (b) side view.

Fig. 6. The mechanical base for glass cover after manufacturing.

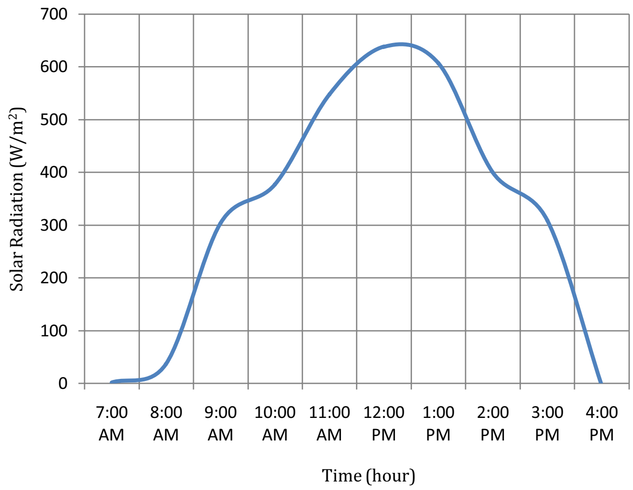

Fig. 7. Solar radiation as a function of time (7/1/2020-Amman).

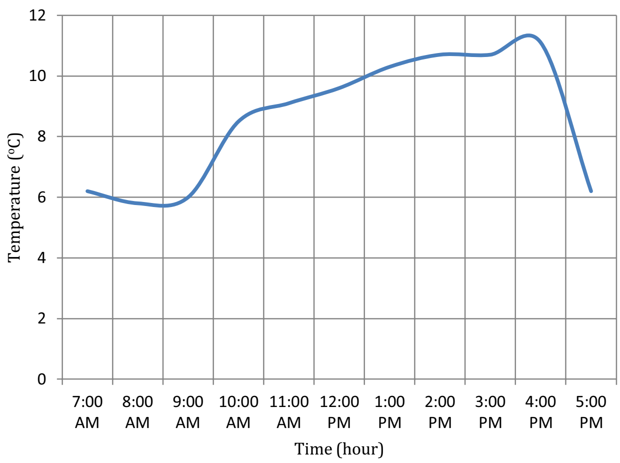

Fig. 8. The ambient temperature as a function of time (7/1/2020-Amman).

give up to 133.45% more production than the conventional solar still.

Abdallah et al. [17] found that the inclusion of internal mirrors to the conventional still has improved the productivity up to 30%, while the step-wise basin enhanced this performance up to 180% and the coupling of the step-wise basin with sun tracking system gave the highest thermal performance with an average of 380%. El-Agouz [21] some modification of a stopped solar still with water circulation using a feeding water tank filled with salted water and seawater. The results of the experimentation show that the performance of the modified stepwise still is higher than that of conventional one by up to 43% and 48% for seawater and salted water with black absorber respectively, 47% and 53% for salted water and seawater with cotton, respectively. Abdallah [23] used a PV generator-powered electrical heater and chamber stepwise basin to the conventional single slope solar still. It was found that the added design modifications improved the productivity of solar still up to 1098%. It is important to notice that the result of last work, which is very huge, depends on using PV generator-powered electrical heater as an external source of power.

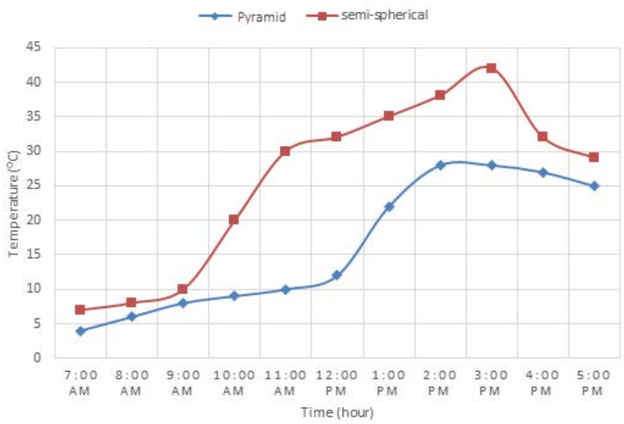

Fig. 9. The temperature inside the basin (7/1/2020-Amman).

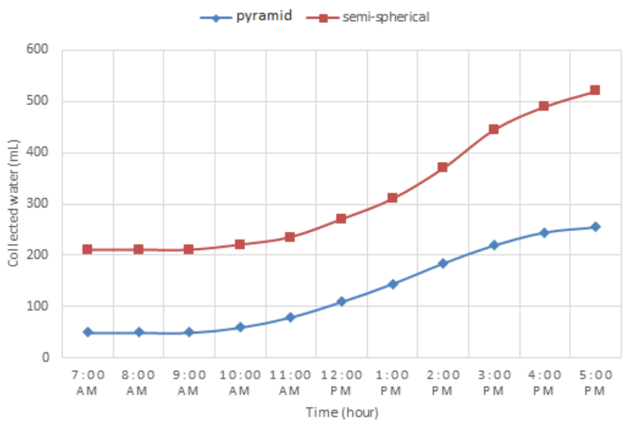

Fig. 10. Distilled water collection (7/1/2020-Amman).

Table 1
Pure water collected using spherical and pyramid stills

Date	Design	Collected water ($L/m^2/d$)	Gain (%)
Day 1 (7/1/2020)	Pyramid	1.275	31.6
	Spherical	1.678	
Day 2 (11/1/2020)	Pyramid	0.875	57.1
	Spherical	1.375	

Comparing the results of the previous works with the results of this work, it is clear that the results of solar still with spherical shape and chamber stepwise basin are satisfied. Of course, these results will be much better if taken during summer time.

5. Conclusions

In this work, two different modifications of the traditional solar still were suggested. One of them involved changing the shape to spherical with chamber stepwise basin, and the other one involved changing the shape into a pyramid with chamber stepwise basin.

An experimental study was performed on typical winter days to investigate the effect of added design modifications on both types. The spherical still gave a higher distilled water production for the first day reaching 31.6%, and for the second day reaching 57.1%. The results are considerable for solar still applications, consequently, this type of solar stills can be used widely for pure water production in the arid zones in the world.

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