Experimental study to enhance the productivity of single-slope single-basin solar still

Abstract: Existence of potable water is considered as one of the important issues that are related to the survival of human life, especially in fresh water scarce areas. So, it is necessary to find a solution to this problem. In the current work, the productivity of fresh water in conventional single-slope single-basin solar still is increased by using two modification methods. The first method is reflecting the solar ray to the still basin by using aluminum foils that are pasted on the interior surfaces of the still walls. This method will enhance the fallen solar rays on basin water and reduce heat losses. The second method increases the evaporation surface area by introducing blackened stainless steel balls with different diameters at the still basin. Balls of two diameters chosen: 5 and 10 mm. The experimental results show that the productivity of solar still with 10 mm-diameter balls is higher than that of the conventional solar still by 38.07%. The corresponding values of the stills with 5 mm-diameter balls and aluminum foils are 31.41 and 14.87%, respectively. The thermal efficiency of the highest productivity solar still is 27.81%. Other stills are characterized by lower thermal efficiencies by various rates.

Keywords: distillation, solar still, solar energy, thermal efficiency, economic feasibility

1 Introduction

For the survival of humanity, fresh water is urgently needed. High ratio of water resources on the earth is oceans and seas. Water from these resources has high salt concentration, which is not suitable for human consumption. The other water resources such as lakes, rivers, marshes, and underground water supply fresh water that is not completely fresh to match the international standard due to the existence of bacteria, viruses, and undesirable impurities. As the population increases, the demand for drinking water also increases. So, the development of water purification systems is important to keep human life and reduce the danger of water scarcity on our planet. Thermal energy, generated from the burning of fossil or hydrocarbon fuels, is widely used to convert brackish or impure water into potable water by the water distillation process. However, this method is not environment-friendly due to air pollution from the exhaust that contains carbon dioxide and monoxide gases. So, to produce fresh water with keeping clean environment, solar energy can be used as thermal energy for the water distillation process. Solar energy is free and abundantly available in most days of the year. Different solar distillation systems are used to produce fresh water, and a solar still is one of them. Solar still is a simple device constructed from an insulated metallic box enclosed by a glass cover. Impure water is kept inside the solar still bottom, which is a rectangular basin with black inside surfaces. Sun ray passes through the transparent cover to reach basin water that is heated and evaporated. Due to the difference between temperatures of the water vapor and cover inside surface, fresh water is produced by water vapor condensation and is collected outside the solar still. Compared with other solar distillation systems, productivity and efficiency of a solar still are low. In several studies, researchers have been attempted to enhance fresh water productivity using a solar still by modifying its design for different operational conditions.

Several methods have been implemented to enhance the productivity of conventional solar still such as increasing its evaporating surface area or using absorbing materials by introducing additional geometries at the still basin. Al-Karaghoul and Minasian [1] concluded that the yield of solar still increased with the use of floating wick that was the cause of the increase in the evaporating surface area. This was also presented in the study by Jani and Modi [2]. Akash et al. [3] observed that the distillate yield of solar still increased by 35 to 60% by using various types of heat storage materials such as rubber mat, black dye, and...
black ink. Nafey et al. [4] modified a conventional solar still by using black rubber sheet with different thicknesses (2, 6, and 10 mm) and black gravel with different sizes (7–12, 12–20, and 20–30) as absorbing materials. Also, the obtained daily distillate output increased by 20% using 10 mm-thick black rubber and by 19% using 20–30 mm black gravel. Naim and Abd El Kawi [5] enhanced the evaporation surface area of solar still by using charcoal particles. Abu-Hijleh and Rababa’h [6] used black and yellow sponge cubes, black steel cubes, and coal cubes to increase fresh water productivity of a conventional solar still. They found that the still distillate output increased by about 255% using sponge cubes.

Velumurugan et al. [7] showed 29.6, 15.3, and 45.5% increase in fresh water productivity of a conventional solar still using wick, sponges, and fins, respectively, at the still basin. Badran [8] compared the operational parameters of a solar still with and without the asphalt basin liner. It was observed that with the modification method, the efficiency of the solar still enhanced up to 51%. Abdallah et al. [9] used three types of absorbing materials at the still basin to modify the performance of solar still. The absorbing materials were uncoated metallic wiry sponge, coated metallic wiry sponge, and black volcanic rocks. Fresh water productivities of the modified solar stills were 28 and 43% using coated and uncoated metallic wiry sponge, respectively, and 60% using black volcanic rocks. Kabeel [10] modified the daily productivity of solar still with four pyramid-shaped sides cover by using a concave jute wick. In the experiments conducted by Sakthivel et al. [11], a conventional solar still was modified by using jute cloths placed at its middle and rear wall. The results showed that the increase in the still efficiency was 8% due to this modification. As well as, the daily productivity of fresh water increased by about 20%. Srivastava and Agrawal [12] conducted an experiment to improve the performance of conventional solar still by using blackened jute cloth at the still basin. In this study, pieces of blackened jute cloth were porous absorbers to modify a conventional solar still. In case of the modified solar still, fresh water production increased by 68 and 35% during clear and cloudy days, respectively. In the study by Srivastava and Agrawal [13], it was observed that the maximum distillate output of modified solar still was about 7.5 kg/m², which was the result of using extended porous fins manufactured from blackened old cotton rags at the still basin. This amount of fresh water was 15% higher than that of the conventional solar still.

Ahmed [14] studied the effect of five different wick materials on performance of conventional solar still. The wicks covered the whole area of the still basin. It was observed that the distilled output value of still with black cotton fabric was the highest. Different energy storage materials were experimentally used in the study by Samuel et al. [15] to increase the distillate output of a conventional solar still. Spherical salt balls and sponge were used in this process. It was shown that the daily distillate output of the conventional solar still was 2.2 kg/m², and it increased due to the effect of the energy storage materials to 3.7 kg/m² with spherical salt balls and 2.7 kg/m² with sponge. Al Alan et al. [16] performed an experiment to enhance the productivity of conventional solar still by using pin-fin wick. The results showed that the efficiency of modified solar still was 55% with higher productivity by 23%. Sellami et al. [17] experimentally evaluated the performance of a solar still by employing blackened sponge sheets of different thicknesses pasted on the still basin. The study found that the decrease in the thickness of sponge sheets led to the increase in the yield of solar still. Fresh water productivity increased by 23.03% with 10 mm-thick sponge sheet, while using 5 mm-thick sponge sheet enhanced the distillate output by 57.77%. The performance of a solar still with vertical rotating wick was presented by Haddad et al. [18]. It was seen that the modified still daily productivity was 7.17 and 5.03 kg/m² in summer and winter, respectively. The experiment was performed by Kabeel et al. [19] to enhance the productivity of conventional solar still by wrapping knitted jute cloths around sand heat energy storages. The daily distillate output of modified solar still was 5.9 kg/m², which was 18% more than that of the conventional solar still.

Rashidi et al. [20] introduced black sponge rubber to a conventional solar still to improve its performance. The amount of fresh water produced by the modified solar still was higher than that of the conventional solar still by 17.35%. Carbon-impregnated foam as a porous absorber and bubble-wrap insulation were used by Arunkumar et al. [21] to modify a conventional solar still. The results showed that the modified solar still provided different amounts of fresh water per the day depending on the materials used: 1.9 L/m² without bubble wrap insulation, 2.3 L/m² with bubble wrap insulation, 3.1 L/m² with both bubble wrap insulation and porous absorber, and 2.2 L/m² with wooden insulation only. V-shaped floating wicks were placed at the basin of conventional solar still in the study by Agrawal and Rana [22]. The productivity and efficiency values in modified solar still were 6.20 kg/m² and 56.62% in summer and 3.23 kg/m² and 47.75% in winter, respectively. Bhargava and Yadav [23] compared thermal performances of solar stills that were modified by using different rectangular-shaped fins wicks: bamboo
cotton, jute, wool, and cotton. The efficiency and daily productivity obtained in the solar still with bamboo cotton wick were 34.5% and 3.03 L/m², respectively. These values were reported as the highest in the experiments. Modi and Modi [24] conducted an experiment to enhance the productivity of single-slope double-basin solar still by employing cloths of jute and black cotton as basin wicks. These wicks were arranged as a small pile over the basin plate of solar still. It was revealed that the distillate output value of the solar still with jute cloth was higher than that of the solar still with the black cotton cloth. Jaafar et al. [25] experimentally enhanced the thermal performance of a single-basin single-slope solar still by introducing various basin wicks. The first wick was an iron mesh with grid space of 25 × 25 mm. The grid space was increased to 50 × 50 mm in the second wick. It was observed that the increase in the efficiency of solar still was 86.65% with the first wick and 72.53% with the second wick.

In the study by Tiwari and Tiwari [26], the effect of the depth of basin water depth on the productivity of solar still was investigated. It was shown that the decrease in the depth of basin water led to an increase in the productivity of solar still. This relation between the productivity of solar still and the basin water depth was also presented by Modi and Modi [24], Agrawal et al. [27], Jaimes et al. [28] and Kumar et al. [29]. It was also documented in the experiment of Jaimes et al. [28] that the increase in the efficiency of solar still was a consequence of the decrease in the thickness of still condenser (glass cover).

In the present work, experiments are performed to modify a conventional single-slope single-basin solar still (referred to hereafter as the CS) by using two modification methods. In the first modification method, the absorber surface of the solar still is increased to enhance the distillate output by the increase in the evaporation surface area. The solar still is modified by using blackened stainless steel balls placed at the still basin. The balls of two sizes are used to present two modified solar stills. The first modified solar still is a single-slope single-basin solar still, in which 10 mm-diameter balls are used (referred to hereafter as the BS1). In the second modified solar still, 5 mm-diameter balls are used to increase the evaporation surface area of single-slope single-basin solar still (referred to hereafter as the BS2). It is known that the increase in the evaporation surface area of solar still will increase fresh water productivity. In the second modification method, 0.5 mm-thick aluminum foils (reflection coefficient near 0.8) are pasted on the inner surfaces of the solar still sides, except the bottom. The act of the aluminum foils is to increase the effective solar radiation by reflecting it back toward the still basin and to reduce the heat loss through the walls. This case study will be referred to hereafter as the MS.

The present study sheds light on the increase in the value of fresh water productivity using aluminum foils or blackened stainless steel balls and finds the relation between the ball size and the distillate output of the solar still. As well as, the experiments are conducted to evaluate the thermal performance of the conventional and modified solar stills during summer by obtaining different parameters. The measured parameters are the hourly temperatures of basin water, the hourly temperatures of vapor, the hourly temperatures of inner and outer surfaces of a glass cover, and the hourly and daily productivities of fresh water. The hourly and total efficiencies of solar stills will be calculated.

2 Experimental setup

The photograph and line diagram of the conventional solar still (CS) are shown in Figures 1 and 2, respectively. The single-slope single-basin solar still was locally manufactured using available materials. Basin and sides of the still were fabricated from 1.5 mm-thick galvanized iron sheets (specific heat capacity and thermal conductivity are 0.462 kJ/kg K and 73 W/m K, respectively) to construct the still box that is open from the top. To minimize heat losses, the outside surfaces of the box were insulated by 25 mm-thick white cork layer (thermal conductivity is 0.045 W/m K). The inside surface of the basin was painted with a muddy black paint (absorptivity 0.88) to enable the maximum absorption of solar radiation. The inner dimensions of the basin are 100 × 100 cm. Height of the higher (right) and lower (left) sides of the box are 528 and 60 mm, respectively. The box was covered with a condensing surface, which is made of 4 mm-thick window type glass sheet (average transmissivity is 0.88). The rubber gasket was applied between the box edges and the glazing cover to avoid the leakage inside vapor. Holes were also provided in the still body to fix thermocouples. To collect the condensed fresh water that flows down the tilted glass cover, a U-shape galvanized steel channel was used as a channel of distillate water. This channel was fitted on the lower side of the still and joined to a container by a flexible tube. The container was located outside the still to collect fresh water, which was then poured in a measuring jar to measure the amount of distillate water at each hour of the experiment. To speed
up the condensate velocity and avoid the re-evaporation state, the collection channel was inclined by \(5^\circ\) toward the container of fresh water. To keep the solar still away from the ground and save its components, a woody frame was designed to cover the whole still except its cover. The basin water depth for all current case studies was 15 mm. One side of the still was joined with a tank of brackish water by a flexible tube. The brackish water tank is a closed plastic storage of water (with salinity of 1,850 ppm).

A blow-off valve was fitted under the basin bottom for cleaning operation after each experiment.

The experiments were carried out in Najaf city, Iraq (latitude 32.0259° N and longitude 44.3463° E). Thus, the tilt angle of the condenser is 32° with the horizontal to obtain the maximum solar radiation on the still throughout the day [30].

To modify the CS, two modification methods were implemented. The first one is the BS1 and BS2, and the other is the MS. To conduct the experiments of BS1 and BS2, stainless steel balls (specific heat capacity and thermal conductivity are 0.468 \(\text{kJ/kg K}\) and 20 \(\text{W/m K}\), respectively) were used and randomly distributed at the still basin of the CS to increase the evaporation surface area. The balls were painted with black muddy paint. For the BS1, 100 of 10 mm-diameter balls were used, while 100 of 5 mm-diameter balls were used for the BS2.

For the MS, 0.5 mm-thick aluminum foils (reflection coefficient near 0.8) were pasted on the inner surfaces of the CS sides, except the bottom. The aluminum foils increase the effectiveness of solar radiation by reflecting it back toward the still basin and reduce the heat loss through the walls. Line diagrams of the BS1, BS2, and MS are illustrated in Figure 3. Properties of the CS and modified solar stills are presented in Table 1.

The experiments were conducted on May 8, 9, 10, and 11, 2021, where the first day was for the CS and the other days were for BS1, BS2 and MS, respectively. The experiments daily time was from 8:00 to 16:00.

To obtain the maximum energy as possible during all experiments, the solar stills were located from the east to the west facing the south direction. The wind speed was hourly
measured by a digital anemometer type (AM-4206M). Temperatures of the ambient, glass cover surfaces, vapor, and basin water were identified at each experimental hour by calibrated K-type thermocouples, which were distributed on different locations inside and outside the solar still. The fallen solar radiation was hourly recorded based on a digital solar radiation meter type (TM-207), which was located on the plane parallel with the glass cover plane, i.e., with the same condenser tilt angle (32°). More details about the currently employed measuring instruments are found in ref. [31]. Table 2 details the accuracy and range of the measuring instruments.

3 Experimental uncertainty analysis

In the present work, measuring instruments are K-type thermocouples for temperature measurements, pyrometer for solar radiation intensity measurement, and anemometer for the wind speed measurement. To identify the experimental uncertainty, these devices are calibrated by comparing their readings with that for standard equipment in the same measurement conditions. It is worth pointing out to show that range and accuracy of instruments can affect accuracy of measurements.

4 Productivity and thermal efficiency

In the current work, the productivity of potable water was collected at each experimental hour. The daily or total productivity, which is the amount of the cumulated fresh

Table 1: Properties of the CS and modified solar stills

| Parameters               | Solar stills | Values | Units |
|--------------------------|--------------|--------|-------|
| Inner length             | All          | 100    | cm    |
| Inner width              | All          | 100    | cm    |
| Right side height        | All          | 528    | mm    |
| Left side height         | All          | 60     | mm    |
| Basin and sides thickness| All          | 1.5    | mm    |
| Cover thickness          | All          | 4      | mm    |
| Water depth              | All          | 15     | mm    |
| Insulation thickness     | All          | 25     | mm    |
| Inclined angle           | All          | 32     | deg.  |
| Aluminum foils thickness | MS           | 0.5    | mm    |
| Balls diameter           | BS1          | 5      | mm    |
|                          | BS2          | 10     | mm    |
| Balls No.                | BS1          | 100    | —     |
|                          | BS2          | 100    | —     |

Table 2: Accuracy and range for the measuring instruments

| Instruments              | Accuracy | Range         |
|--------------------------|----------|---------------|
| Thermocouples            | ±0.1°C   | 0–100 °C      |
| Solar radiation meter    | ±5% W/m² | 0–1,400 W/m²  |
| Anemometer               | ±1.8% m/s| 0.4–30 m/s    |
| Measuring jar            | ±5 mL    | 2,000 mL      |
The total productivity of fresh water from the still is calculated from:

$$P_d = \sum \frac{d.w.h}{1} p_h.$$  \hspace{1cm} (1)

The fresh water productivity enhancement ($p_{enh}$) of solar still is evaluated as:

$$p_{enh} = \frac{(P_d)_m - (P_d)_c}{(P_d)_c} \times 100\%.$$  \hspace{1cm} (2)

($P_d)_m$ and ($P_d)_c$ are the total productivity of fresh water from the modified and conventional solar still, respectively.

As presented in refs [32–35], the hourly thermal efficiency of solar still is defined as the ratio of the heat transfer per unit mass ($q_e$) by evaporation–condensation in the still to the incident solar radiation ($I$) in the still.

$$\eta = \frac{q_e}{I} \times 100\% = \frac{h_{ewg}(T_w - T_{gi})}{I} \times 100\%.$$  \hspace{1cm} (3)

The hourly productivity of fresh water in (kg/h) is defined as follows:

$$p_h = \frac{h_{ewg}A_g(T_w - T_{gi})}{L} \times 3,600.$$  \hspace{1cm} (4)

So, the hourly thermal efficiency of solar still is calculated as follows:

$$\eta = \frac{p_h \times L}{A_g \times I \times 3,600} \times 100\%.$$  \hspace{1cm} (5)

Thus, the total thermal efficiency of solar still is expressed as follows:

$$\eta_t = \frac{P_d \times L_{av}}{A_g \times \sum \frac{d.w.h}{1} l \times 3,600} \times 100\%.$$  \hspace{1cm} (6)

$L$ is calculated based on ref. [36] in J/kg as follows or using online tables [37]:

$$L = (2503.3 - 2.398 \times T_w) \times 10^3.$$  \hspace{1cm} (7)

5 Results and discussion

The ambient conditions for the experimental days are shown in Figure 7. It is clearly seen that there is no considerable difference among the hourly temperatures and solar radiation at each experimental hour for the experiments days. This is because the experiments were carried out on consecutive days in the same month (May 8–11, 2021). So, it can be concluded that the difference between the results of the CS and modified solar stills is due to the effect of the modification methods on the performance of still, i.e., there is no effect on the results as the experiments were conducted on different days.

The measured results for all current case studies are detailed in Table 3 that presents basin water temperature ($T_w$), vapor temperature ($T_v$), and $T_{gi}$ and $T_{go}$ as temperatures of inside and outside surfaces of the glass cover, respectively.

For the CS, the basin water temperature at the start point of the experiment was approximately equal to other still temperatures as shown in Figure 8. Actually, this behavior was recorded for the other stills. During the experimental period that was extended from 8:00 to 16:00, the maximum basin water temperature was recorded at 13:00 for all stills as shown in Figure 9. This behavior of temperature was also noticed for all other still temperatures as shown in Figures 10–12 that present the variation of temperatures of vapor, inside glass cover, and outside glass cover, respectively, with local time of experiments.

Distributions of the temperatures at different points of the current stills that shown in Figures 9–12 provide comparisons among different temperatures of the stills. It is clearly seen that at 8:00, there was no considerable difference among all temperatures of all current stills. The reason for that is at 8:00, the experiments just started and the recorded temperatures were very close to the ambient temperatures, which were approximately similar for all days of the experiments. At the next hour, temperature difference shows that basin water and vapor temperatures of the MS were higher than that of other stills as shown in Figures 9–12. That is because the aluminum foils that were pasted on inside surfaces of the MS reduced the heat losses through the still walls. In addition, the presence of aluminum foils in the MS increased the solar energy that was absorbed by the basin water due to the solar ray.
reflecting process. Regarding the BS1 and BS2, it is normal for their temperatures to be less than the MS temperatures because the stainless steel balls absorbed some of the solar energy that reached the basin water during this time.

In the interval between 10:00 and 16:00, difference in temperatures of all parameters for all stills becomes clear and significant as shown in Figures 9–12. It is clearly shown that temperatures of basin water, vapor and condenser sides of the BS2 were the highest compared with those for other stills. The maximum values of measured Tw, Tv, Tgi, and Tgo in BS2 were 76.1, 70.4, 66.2, and 65.4 °C, respectively. The temperatures difference between the BS2 and BS1 was lower than that between the BS2 and MS, suggesting that using the stainless steel balls increased temperatures of still parameters more than using aluminum foils. The lowest recorded temperatures between 10:00 and 16:00 were for the CS. This means that all the current proposed modification methods are working to improve the performance of the conventional solar still. This can be proved by the increase in their all parameter temperatures compared with those for the CS.

Regarding the effect of the stainless steel ball sizes used in the BS1 and BS2, there is no doubt that the increase in the ball size improves the performance of the solar still. This is shown in the increase in the temperatures of still parameters. This is shown in Figures 9–12. The fact that use of the stainless steel balls improves the performance of solar still is attributed to the increase in the evaporation surface area of the BS2 and BS1 with respect to the MS and CS. In the early time of the experiments, the stainless steel balls work as energy storages by absorbing some of falling solar energy. Then, this energy is released to the basin water leading to increase its temperature, which is a consequence of the increase in the temperature of other parameter. This is the action of increasing the evaporation surface area of the still basin.

The daily and hourly productivity of the current solar stills are illustrated in Figures 13 and 14, respectively. The BS2 total productivity of fresh water was 2.154 L. In the CS, MS, and BS1, the corresponding values were 1.56, 1.792, and 2.05 L, respectively. This is clearly shown in Figure 10. This result is of course related to the highest performance of the BS2 that is obtained from the highest temperatures ranges of this still.

Figure 14 shows the variation of fresh water productivity of all current case studies with the experimental time. The maximum collected pure water was in the BS2 at 13:00. Its amount was 375 mL, while the corresponding values for the CS, MS, and BS1 were 295, 310, and 358 mL, respectively. It is also shown in Figure 14 that the difference in fresh water productivity between the BS2 and BS1 at all experimental hours is small with respect to the other stills. This is due to the modification method implemented in the BS2 and BS1, which was similar expect one difference that was related to the ball size, which affected the still performance. The productivity enhancement of fresh water is presented in Figure 15. As shown in this figure, the productivity enhancement value was 38.07% for the BS2.
The variation in the hourly thermal efficiency with the experimental time that is illustrated in Figure 16 refers to the close agreement between the values of this parameter of the BS1 and BS2. This is because the same modification method was used in the BS1 and BS2 (using the stainless steel balls). However, the BS2 thermal efficiencies are more than BS1 thermal efficiencies at all hours as an indication of the effect of the ball size on the solar still performance. The comparison among the total thermal efficiency of the stills is presented in Figure 17. It is clearly seen that the increase in the total thermal efficiency using the MS, BS1, and BS2 is 2.94, 6.18, and 7.43%, respectively. This is to indicate that the corresponding values were 31.41 and 14.87% for the BS1 and MS, respectively.

The variation in the hourly thermal efficiency with the experimental time that is illustrated in Figure 16 refers to the close agreement between the values of this parameter of the BS1 and BS2. This is because the same modification method was used in the BS1 and BS2 (using the stainless steel balls). However, the BS2 thermal efficiencies are more than BS1 thermal efficiencies at all hours as an indication of the effect of the ball size on the solar still performance. The comparison among the total thermal efficiency of the stills is presented in Figure 17. It is clearly seen that the increase in the total thermal efficiency using the MS, BS1, and BS2 is 2.94, 6.18, and 7.43%, respectively. This is to indicate that
using the stainless steel balls has a considerable effect to improve the performance of solar still compared with using the aluminum foils.

6 Economic feasibility

To shed a light on economic feasibility of the conventional and modified solar stills, their manufacturing costs and yearly productivity of fresh water will be considered. The working life span of the current solar stills is five years. During that period, the maintenance cost for each still is estimated as 20% of its manufacturing cost. Total costs (including materials, manufacturing, and maintenance...
The costs (USD) of the present solar still systems are detailed in Table 4.

In Iraq, summer months are from May to October. These months are characterized with high ranges of ambient temperatures and sunny days. It can be assumed that the daily fresh water productivity that was obtained from the current experiments is similar for all days of summer. Due to ambient temperature reduction and most partially cloudy days (in general) in the other months of the year, their amount of produced potable water is estimated to be half of that yielded in summer. So, the yearly production of pure water from the current solar stills can be estimated as presented in Table 5.

From Tables 4 and 5, we can calculate the cost of one liter of produced fresh water during the working life span of the still as follows:

\[
\text{Cost} = \frac{\text{Still total cost}}{\text{Produced water amount}}
\]  

Table 4: Total costs of the solar stills

| Items                  | CS  | MS  | BS1 | BS2 |
|------------------------|-----|-----|-----|-----|
| Still                  | 75  | 75  | 75  | 75  |
| Aluminum foils         | —   | 15  | —   | —   |
| Stainless steel balls  | —   | —   | 10  | 15  |
| Woody frame            | 60  | 60  | 60  | 60  |
| Brackish water tank    | 10  | 10  | 10  | 10  |
| Other parts            | 20  | 20  | 20  | 20  |
| Maintenance            | 33  | 36  | 35  | 36  |
| Total cost (USD)       | 198 | 216 | 210 | 216 |

Table 5: Expected fresh water productivity from the solar stills

| Productivity (L)       | CS  | MS  | BS1 | BS2 |
|------------------------|-----|-----|-----|-----|
| Per year               | 421.2 | 483.84 | 553.5 | 581.58 |
| Per working life span  | 2,106 | 2419.2 | 2767.5 | 2907.9 |

Table 6: Economic feasibility of the solar stills

| Parameters                     | Current solar stills |
|-------------------------------|----------------------|
| Production cost (USD/L)       | 0.094 | 0.089 | 0.076 | 0.074 |
| Money saving (USD)            | 223.24 | 268.53 | 343.17 | 366.39 |
| Payback period (years)        | 2.350 | 2.237 | 1.897 | 1.857 |
The cost of producing one liter of fresh water from the current solar stills during their working life span is shown in Table 6. The price of one liter of the potable water in the markets is 0.2 USD. So, the money saving from using each current solar still is detailed in Table 6. In addition, Table 6 presents the payback period for each solar still. The payback period is calculated according to \[ \text{Payback period} = \frac{\text{Still total cost}}{\text{Price of yearly purchasing water}}. \] (9)

In Table 6, it is clearly seen that investment in the field of fresh water production using BS2 is the best choice. The payback period for the BS2 is less than that of the other current solar stills.

7 Conclusion

The current study presents different modification methods to enhance the performance of conventional solar still. It is concluded that the BS2 is the best to increase the total productivity of fresh water and thermal efficiency by 0.594 L and 7.43%, respectively. It is also shown that the increase in the evaporation surface area using the BS1 and BS2 provides higher pure water production than that of reflecting the solar radiation back to the still basin, which is implemented in the MS. However, the evaporation surface area modification method (using of stainless steel balls) is controlled by the ball sizes. The BS2, followed by the BS1, MS, and CS, has the highest temperatures for still basin water, vapor, and glass cover sides. This is the reason for the highest productivity and thermal efficiency of the BS2.

Economic feasibility of the current solar stills is also performed. The cost analysis indicates that the payback period of the BS2 is 1.857 years, which is lesser than that of the other stills. The corresponding values are 2.350, 2.237, and 1.897 years for the CS, MS, and BS1, respectively.

For further work, it is suggested to use different geometries with the modification method that is associated with the increasing evaporation surface area such as cylinders and cones. In addition, it is preferred to change the size of these geometries to investigate its effect on the productivity of fresh water in the solar still.

### Nomenclature

| Symbols | Definition                                      | Units   |
|---------|-------------------------------------------------|---------|
| \( A_b \) | basin area                                      | m²      |
| \( A_g \) | glass cover area                                | m²      |
| \( h_{_{ewg}} \) | evaporative heat transfer coefficient from water surface to glass cover | W/m² K |
| \( I \) | solar radiation intensity                       | W/m²    |
| \( L \) | latent heat of water evaporation                | kJ/kg   |
| \( L_{av} \) | average latent heat of water evaporation        | kJ/kg   |
| \( P_d \) | total productivity of fresh water               | L/day   |
| \( P_h \) | hourly productivity of fresh water              | L/hr    |
| \( T_{gi} \) | temperature of inside surface of glass cover    | °C      |
| \( T_{go} \) | temperature of outside surface of glass cover   | °C      |
| \( T_{gv} \) | temperature of vapor                            | °C      |
| \( T_{gw} \) | temperature of basin water                      | °C      |

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