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Performance Evaluation Investigation for Conventional Solar Still with Different Additives

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ABSTRACT

The demand for freshwater is on the rise due to a multitude of human activities and a rapidly expanding global population. The yielding of pure water heavily depends on the utilization of traditional sources of energy, which in turn contributes to environmental contamination. Consequently, there is a necessity to explore alternative options, such as clean energy (specifically solar energy). Numerous systems for desalination have been devised to confront this inadequacy. One such system is the Conventional Solar Still (CSS), which is easy to production, operate and continue, but the limited production has prompted researchers to consider various improvements to increase the productivity of the still. This study elucidates a sustainable way to diminishing the duration required for the evaporation process, thereby augmenting the efficiency of clean water solar energy production. All investigates were operated under the local weather circumstances of Najaf city, central-western Iraq. The peak time for the experimental work is 14:00 PM. The Everyday output of the CSS, Modified Solar Still 1 (MSS1) and Modified Solar Still 2 (MSS2) is 2.225, 2.870 and 3.939 L/m2.day, respectively. The outcomes displayed that the maximum value of the thermal efficiency and the exergy efficiency were obtained estimated at 29.34% and 3.96% for CSS, 40.1% and 4.85% for MSS1 and 59.45% and 6.75% for MSS2. While the cost of 1 litter of pure water improved by 14.67% for MSS1 and 40.02% for MSS2 as compared with that from CSS.

1. Introduction

One of the biggest global problems is the lack of readily available drinking water. A large number of people around the world suffer from a lack of fresh water supplies, and the African population represents 31% of them, followed by the populations of Europe, Asia, and America, with rates of 2%, 25%, and 7%, respectively [1]. In rural areas, accessing affordable clean water is a challenge. Solar desalination using a basin still presents a sustainable solution to this issue. While the basin still is straightforward to construct, its production capacity is hindered by cost inefficiencies. Various design modifications have been explored to enhance productivity [2].

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There are a number of different factors that affect the effectiveness and performance of a device such as solar radiation intensity, weather conditions, and design. The main factor in refining the output of a solar still is increasing the temperature variation among the water mass (T_w) and the inner side of the cover ($T_{g,in}$). This has made it a goal for researchers to improve the output of solar stills. Some of them delved into raising the condensation process [3–9], some of them went to improving the evaporation process [10–27], and others went to improving both processes to reach the highest level of improvement in the yield of the device, as in [28–36].

Mu et al. (2019) [37] studied the conventional model's actual performance coupled with a Fresnel lens. The results showed that the optimization used significantly enhanced the evaporation process and production. Meanwhile, Jaafar (2020) [38] studied the utilization of a solar-powered tank equipped with a conventional still, as demonstrated in Figure 1, in order to enhance the evaporation process. This intervention resulted in a significant enhancement of fresh water productivity by 48.83%.

Fig. 1. Solar still connected with solar energy tank [38].

Dhivagar et al. (2022) [39] significantly improved the efficiency of a conventional solar still by incorporating a porous thermal storage medium. Their findings indicated that the modified solar still achieved daily water productivity and exergy efficiency improvements of 31.2% and 19.04%, respectively.

Abdulridha et al. (2024) [40] conducted an experimental investigation to boost the output of a conventional solar still using a finned tube solar collector. Their results showed that the productivity of the reference model was 2.886 L/m^2.day, while the modified model achieved 4.766 L/m^2.day. In another study, Abdulridha et al. (2024) [41] experimentally assessed the effectiveness of a solar distiller by enhancing the vaporization process with two distinct types of collectors: one with a finned tube absorber and a conventional one. Their outcomes demonstrated a 65.12% improvement in productivity when utilizing the finned tube absorber.

This paper presents a practical study comparing the performance of two modified stills (MSS1 and MSS2) with a reference conventional still (CSS). MSS1's basin is equipped with 25 longitudinal aluminum fins (C_p = 0.9 J/g.°C and k=210 W/m-K), each featuring two equal sides with a 90^o angle. The fins are 0.95 m in length. MSS2's basin contains 50 cast iron serrated shafts (C_p = 390 J/kg.°C and k=46 W/m-K), each 1 cm in diameter and 5 cm in length. These specific additives have received limited attention in prior research. Experimental investigations were conducted in April, from 8:00 a.m. to 5:00 p.m., under the actual climatic conditions of Najaf, Iraq.

2. Experimentation

In the experiments, three identical single-slope distillers are fabricated. The stills were made of a 1.5 mm thick square iron plate with an area of 1 square meter. Polystyrene is used to insulate all sides of distillers, to reduce the loss of energy collected inner the still. The thermal conductivity of the polystyrene is 0.03 W/m.K [42]. A traditional glass sheet with a 4 mm thickness and 88% transmissivity is used and inclined at an angle of 32o with horizontal cover the solar stills, which were directed towards the south to attract the largest amount of solar radiation. As shown in Figure 2, the captures are installed on an iron frame with a height of 60 cm.

Temperatures will be collated every hour employing calibrated K-type thermocouples across stills (plate, vapor, water, inner and outer glass surfaces). Seven thermocouples were used for every still to measure the temperatures. As shown in Figure 3a, a digital monitor connected to the thermocouples displays the measured temperatures. The SM206 (Figure 3b) measures solar radiation hourly, with a reading range of up to 1400 W/m². The radiation meter is inclined similarly to the glass cover to ensure precise radiation readings. Wind speed is observed each hour with a GM-8902 anemometer (Figure 3c), with a reading range up to 89 m/s. A graduated glass flask with a capacity of 1.5 L is utilized to collect and gauge the yield.

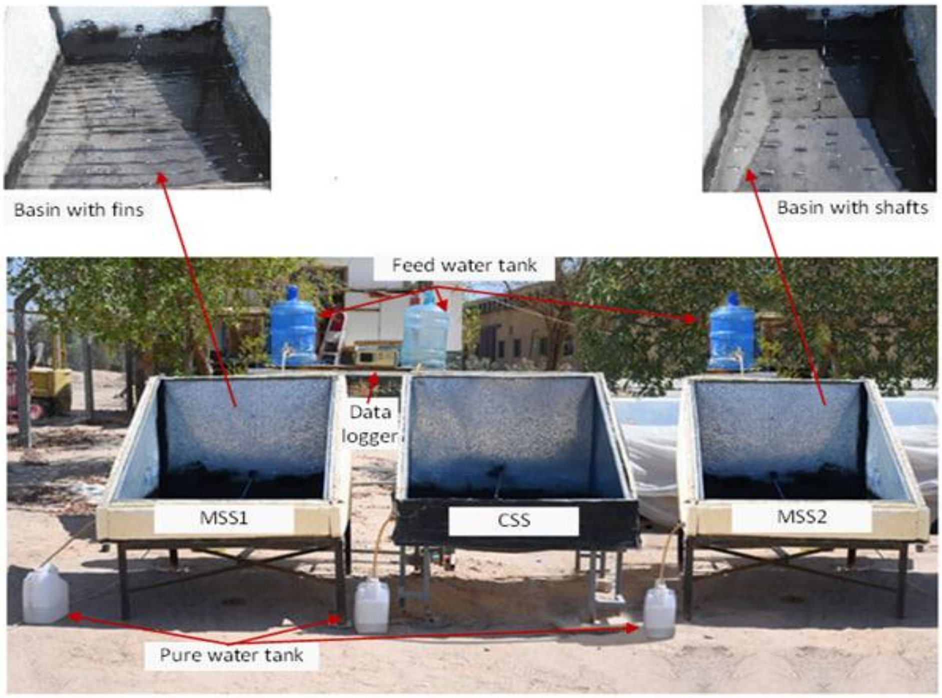

Fig. 2. Front view of the experiment work

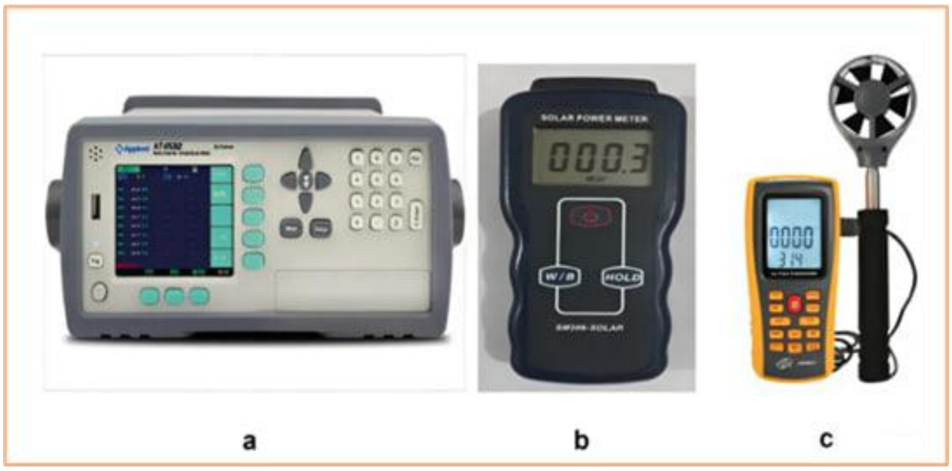

Fig. 3. a) digital data logger (AT4532), b) solar power meter SM206, c) GM-8902 anemometer

The distribution and locations name of thermocouples, along each solar still, are as shown in Figure 4 and Table 1.

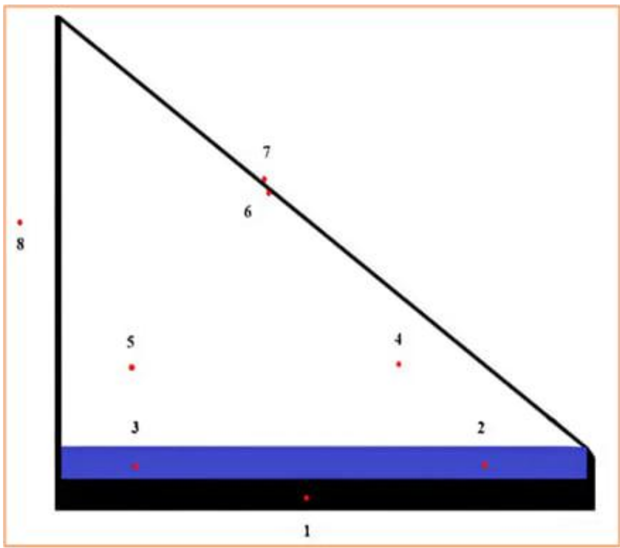

Fig. 4. Location of the thermocouples

Table 1 Locations name of the thermocouples

Thermocouples	1	2,3	4,5	6	7	8
Locations	Absorber Part	Water layer	Vapor region	In-Glass cover	Out- Glass cover	Ambient

Table 2 displays the accuracy of the devices utilized in the practical aspect. The process of determining standard uncertainties involves evaluating linear variance within the data set produced by the device. As such, it is conventionally expressed as $a/\sqrt{3}$, with (a) demonstrates the accuracy of measuring equipment [43].

Table 2. Uncertainty about measuring equipment.

Equipment	Accuracy	Range	Uncertainty
Thermocouples	± 1.1 °C	$0 - 300\ C^o$	0.690 °C
Radiation meter-SM06	± 10.2 W/m^2	$0 - 3999\ w/m^2$	5.75 W/m^2
Wind speed meter- GM-8902	$\pm 0.18\ m/s$	0 – 90 m/s	$0.114\ m/s$
Graduated transparent collection bottle	$\pm 5\ ml$	0 – 2 liter	1.2 ml

2.1 Experimental Procedures

All experiments were conducted in the April 2023 at Najaf engineering technical college / Iraq. To obtain accurate results a direct compression was used by conducting experiments with three rigs in the same position and time to sure the solar stills are working at the same conditions. 22 K–type calibrated thermocouples and digital monitor utilized to data capture form 08:00 AM to 17:00 PM and the radiation, wind speed and productivity of the pure water were measured hourly.

Solar stills for distillation were oriented to the southerly direction, with the cover at 32o to ensure high solar radiation reception. The level of the water inside stills is adjusted to 1 cm using an inverted bottle method. The water will commence the process of upward evaporation when the water temperature surpasses a specific threshold and by the prevailing conditions. Coming into contact with the inclined glass surface, characterized by a lower temperature. This interaction results in vapor condensation on the cover's inner surface, manifesting as droplets. Subsequently, these droplets descend downward due to the inclination of the cover towards the collection channel, and then finally collected into the graduated flask.

2.1.1 Thermal efficiency analysis

Depending on the area of the part exposed to solar radiation (A), the amount of available radiation (I), and the yield value obtained (m), an accurate estimate of the thermal efficiency (η_{th}) can be made as follows [44]:

$$\eta_{th} = \frac{\dot{m} * h_{fg}}{A * I * 3600} * 100 \quad (1)$$

2.1.2 Exergy efficiency analysis

The exergy analysis for the still is conducted through the utilization of the governing equations established upon the principles of the 2nd of thermodynamics. Consequently, the overall formula of the exergy balance can be articulated as described in the subsequent manner [40].

$$E_{x,dest} = E_{x,in} + E_{x,out} \quad (2)$$

$$E_{x,in} = E_{x,sun} = I_t A_b [1 - \frac{4}{3}\left(\frac{T_{amb}+273.16}{T_{sun}}\right) + \frac{1}{3}\left(\frac{T_{amb}+273.16}{T_{sun}}\right)^4] \quad (3)$$

$$E_{x,out} = E_{x,evap} = \frac{m_{evap}\, h_{fg}}{3600}[1 - \left(\frac{T_{amb}+273.16}{T_w+273.16}\right)] \quad (4)$$

$$h_{fg} = 2.4935 * 10^6 * (1 - 9.4779 * 10^{-4} * T_{w,b} + 1.3132 * 10^{-7} * T_{w,b}^2 - 4.7974 * 10^{-9} * T_{w,b}^3) \quad (5)$$

where, A_ (b)is the basin area, I_(t) is the radiation (SR) direct on the absorber, and T_sun is the sun's temperature, Its value is about 6000 K. h fg is Latent heat of vaporization. m_evap is amount of evaporative water. T_w is temperature of water. In a related context, the exergy efficiency can be expressed as the ratio of the obtained yield to the consumed amount of energy, as follows:

$$\eta_{EX} = \frac{E_{x,out}}{E_{x,in}} = \frac{E_{x,evap}}{E_{x,sun}} \quad (6)$$

3. Results and Discussion

Experiments for CSS, MSS1 and MSS2 were conducted over several days in the month of April to obtain accurate outcomes for the behaviour and performance of the stills. as the weather conditions were almost similar during the days of April 15-18. To show the most accurate results, the results of the experiments on April 16 are presented.

Fig. 5 lists the available climatic conditions and their behaviour during the experiment, including solar radiation, air temperature, and airspeed, for April 16. It is clear from the figure that the SR increased gradually and touches its extreme value approximately at 12:00 PM, and then it slowly initiates to reduction until the end of the experiment time. Also, the behaviour of wind speed and temperature is almost consistent with the behaviour of SR.

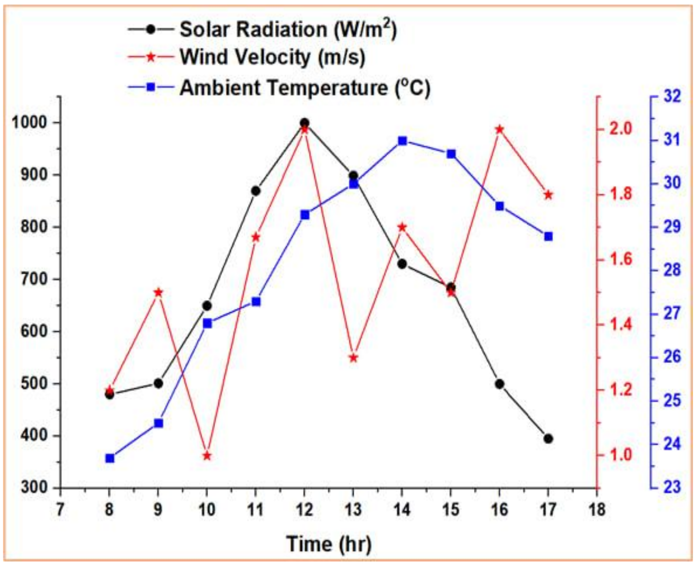

Fig. 5. Variation of SR, airspeed and air temperature with time on April 16

Figures 6,7, and 8 display the behaviour of absorber, saline solution, steam, inner and outer transparent cover temperatures along the period of experiments for CSS, MSS1 and MSS2. These figures show that temperatures are directly proportional to the increase in solar radiation intensity, as they behave similarly to the available radiation in increasing and decreasing. The figures conclusively show that the modified solar stills experience a temperature enhancement compared to the conventional stills, especially when the solar radiation value is high after 11:00 a.m. This is due to the use of additives in the solar still basins.

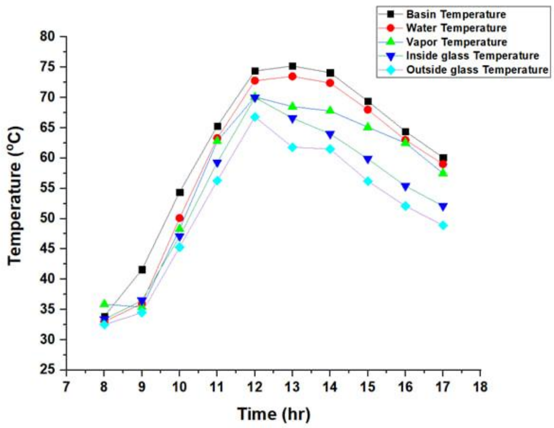

Fig. 6. Variation of temperature for CSS

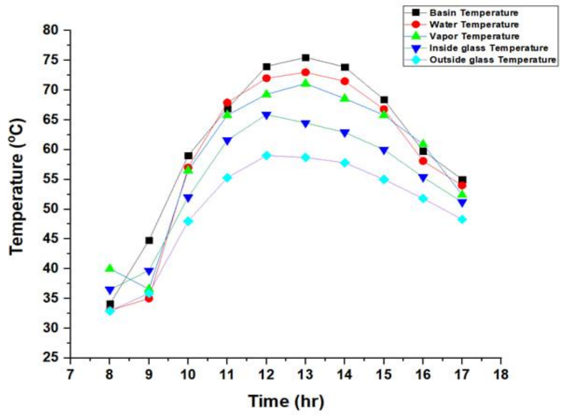

Fig. 7. Variation of temperature for MSS1

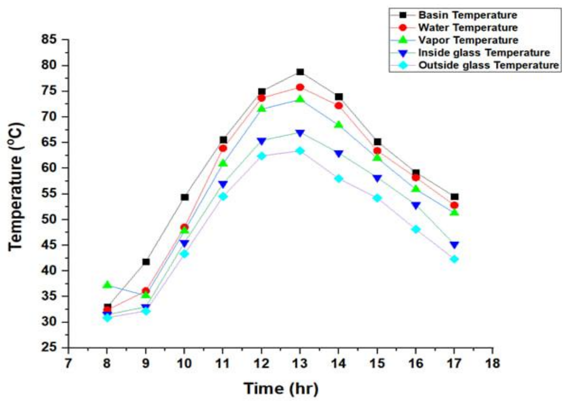

Fig. 8. Variation of temperature for MSS2

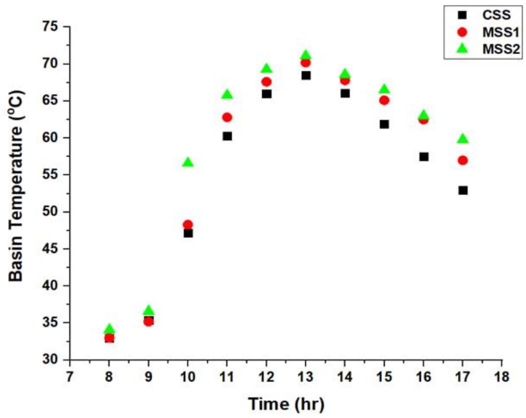

Fig. 9. Brine layer temperature variations during the experiment for CSS, MSS1, and MSS2.

Figure 9 illustrates the **basin temperature behavior over time** for the Conventional Solar Still (CSS), Modified Solar Still 1 (MSS1), and Modified Solar Still 2 (MSS2). Significantly, the figure shows that the brine layer temperature consistently rises, peaking around 1 p.m., before gradually decreasing. Additionally, the presence of additives in the modified stills leads to **higher temperatures in MSS2 compared to the other stills**, which is attributed to the inclusion of shafts.

Figures 10 and 11 present the **hourly and cumulative water productivities** for MSS1 and MSS2 in comparison to the CSS during the experimental period. Productivity increased by **28.54% for MSS1 and 77.03% for MSS2** when compared to the CSS. Furthermore, to highlight the significance of this investigation, the productivity achieved in this study was also compared with findings from other research conducted in the same area, as detailed in Table 3.

Figure 9 shows the basin temperature behaviour with time for CSS, MSS1 and MSS2. Importantly, the figure shows that the brine layer temperature increases gradually over time, reaching its maximum at 1 p.m., and then begins to decrease sequentially. Also, the figure depicts with the presence of additives, the higher temperature is for MSS2 than the other stills, due to the presence of shafts.

The hourly and cumulative productivities of water for both MSS1 and MSS2 comparing to that of CSS during the day of experiments as shown in figures 10 and 11. The productivity increasing by 28.54% for MSS1 and 77.03% for MSS2 as compared to that of CSS. Also, the productivity of the current study was also compared with the productivity of other works conducted in the same work area, to show the importance of the current investigation, as presented in Table 3.

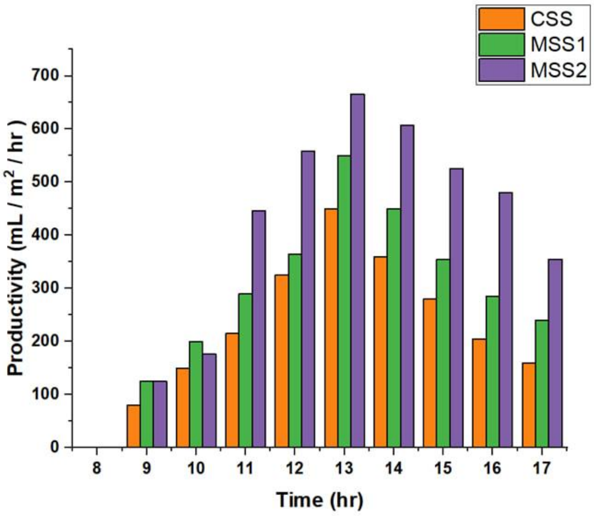

Fig. 10. Comparison of the productivity achieved by the models used in the practical aspect.

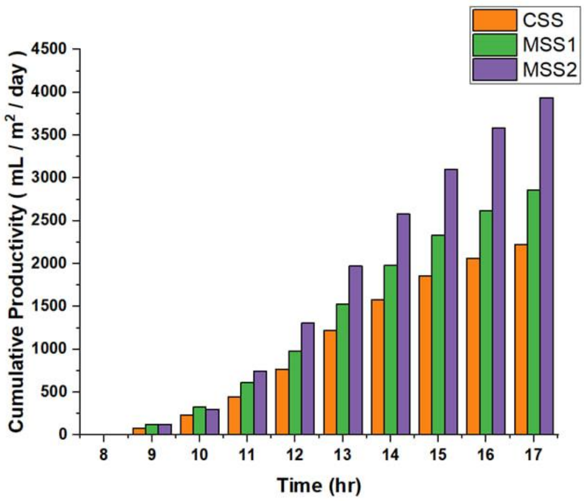

Fig. 11. Comparison of the daily productivity achieved by the models used in the practical aspect.

Figure 12 illustrates the **thermal efficiency** variations of the solar stills (CSS, MSS1, and MSS2) throughout the experimental period. As shown, thermal efficiency increases over time, which directly correlates with the rise in solar radiation. Additionally, the use of additives clearly boosts thermal efficiency, with the highest efficiency observed when using **shafts in the solar still basin** (MSS2). Notably, thermal efficiency continues to increase even after solar radiation declines, which is attributed to the **heat storage capacity of the additives** within the basin.

Meanwhile, Figure 13 presents the exergy efficiency behavior of CSS, MSS1, and MSS2 over the experimental duration. The figure clearly demonstrates a direct relationship between exergy efficiency and solar radiation, as both peak at midday. As solar radiation decreases, exergy values noticeably decline. Furthermore, it's evident that MSS2 exhibits higher exergy efficiency compared to the other two stills.

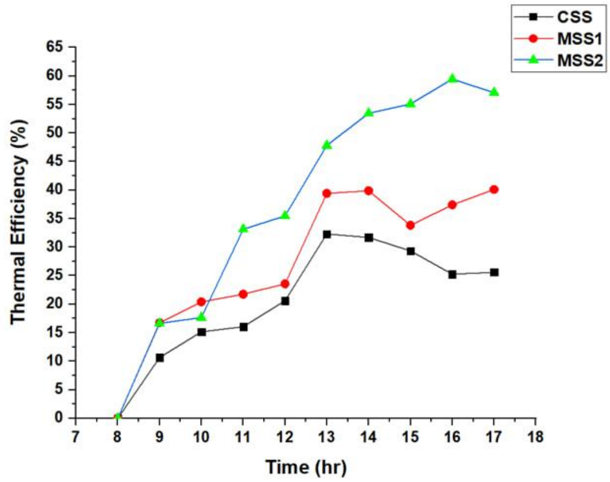

Fig. 12. Thermal efficiency for CSS, MSS1 and MSS2.

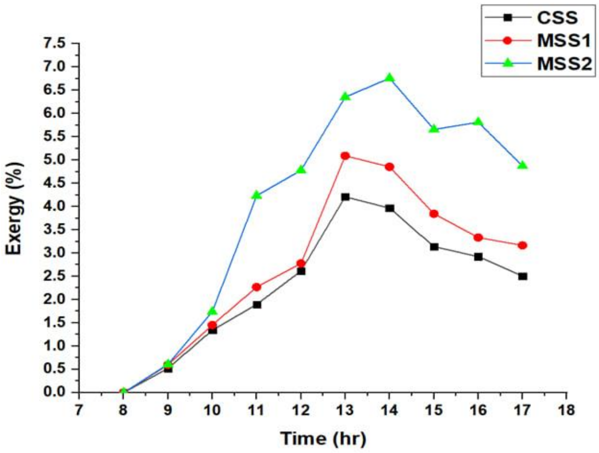

Fig. 13. Exergy for CSS, MSS1 and MSS2.

The productivity of this study was also compared with that of other research conducted in the same area, as shown in Table 3. This comparison highlights the significance of the current investigation.

Table 3. compression of the current study and others studies

References	Data / Country	Technique	% Enhancement	Productivity ($L/m^2/day$)
Jaafar and Hameed [45]	2021 / Iraq	Using Solar still with copper pipe	90.09%	(50% filling) 4.03
Fadhel et all. [46]	2021/Iraq	PTC with nanofluid	42.2%	8.74
Abdulridha et all. [40]	2024 / Iraq	Finned tube solar collector with still	65.12%	4.766
Hassanain Ghani Hameed [47]	2022 / Iraq	Fins and Colling cover	61.3%	3.531
Current Study	April (2023) / Iraq	MSS1	28.54%	2.860
		MSS2	77.03%	3.939

The total cost of a solar still can be determined by considering two primary components: fixed costs and variable costs.

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1. Fixed Costs (F): These are one-time expenses associated with the initial design and construction of the solar still, such as the cost of materials and fabrication.
2. Variable Costs (V): These are ongoing costs that depend on the daily operation of the still, such as maintenance and cleaning.

The total cost, C, is calculated by summing the variable and fixed costs, as shown in Equation (7):

$$C \text{ (total cost)} = V \text{(variable cost)} + F \text{ (fixed cost)} \quad (7)$$

In this analysis, the costs are estimated based on the daily productivity and the assumed lifetime of the still. To facilitate the calculation of the total cost, the following assumptions were made by the authors:

1. The solar still operates for 300 days per year.
2. The lifetime of the still is 10 years.
3. The variable cost is assumed to be 30% of the fixed cost per year, i.e., V=0.3×F.

Table 4 presents the fixed and total costs for three different solar still designs: the Conventional Solar Still (CSS), a modified CSS with Fins (CSS-Fins), and a modified CSS with Shafts (CSS-Shafts). The cost per liter of distilled water is calculated for each design as shown as follows:

1. Conventional Solar Still (CSS)
   - Fixed Cost (F): The fixed cost for a 1 m2 CSS is $64.5.
   - Total Cost (C): Using Equation (7) and accounting for the 10-year lifetime, the total cost is: $C = F + (V \times \text{lifetime}) = 64.5 + (0.3 \times 64.5 \times 10) = 64.5 + 193.5 = $258
   - Total Water Production: With an average daily productivity of 2.225 L/m^2 per day, the total production over the 10-year lifetime is: Total Production = 2.225 L/m^2/day × 300 days/year × 10 years = 6675 L
   - Cost per Liter: The cost of producing one liter of distilled water is determined by dividing the total cost by the total production. Cost per Liter = $258 / 6675 L = $0.03865/L
2. Conventional Solar Still with Fins (CSS-Fins)
   - Fixed Cost (F): The fixed cost for a 1 m2 CSS with fins is $71.
   - Total Cost (C): $C = 71 + (0.3 \times 71 \times 10) = 71 + 213 = $284
   - Total Water Production: With an average daily productivity of 2.870 L/m^2 per day, the total production is: Total Production = 2.870 L/m^2/day × 300 days/year × 10 years = 8610 L
   - Cost per Liter: Cost per Liter = $284 / 8610 L = $0.03298/L
3. Conventional Solar Still with Shafts (CSS-Shafts)
   - Fixed Cost (F): The fixed cost for a 1 m2 CSS with shafts is $68.5.
   - Total Cost (C): $C = 68.5 + (0.3 \times 68.5 \times 10) = 68.5 + 205.5 = $274
   - Total Water Production: With an average daily productivity of 3.939 L/m^2 per day, the total production is: Total Production = 3.939 L/m^2/day × 300 days/year × 10 years = 11817 L
   - Cost per Liter: Cost per Liter = $274 / 11817 L = $0.02318/L

4. Conclusions

This study investigates the performance of two modified solar still models (MSS1 and MSS2) compared to a conventional solar still (CSS). MSS1 is a CSS integrated with fins, while MSS2 is a CSS integrated with shafts. Under environmental conditions, the experimental results showed that both

MSS1 and MSS2 significantly increased the basin water temperature. This indicates their potential for efficient thermal energy conversion. This temperature increase positively impacts the still's thermal conditions, which then reduces the water evaporation time in the basin and enhances overall operational efficiency. The daily yield of the solar still increased by as much as 28.54% with the use of fins in the CSS basin, and by an impressive 77.03% with the use of shafts. The average thermal efficiency of the conventional solar still, which was 25%, also improved with these additives. It increased to 30% with fins and 50% with shafts. Similarly, the conventional solar still's average exergy efficiency improved from 3.5% to 4.8% with fins and 6.9% with shafts. In terms of cost, the conventional distiller produced water at $0.03865 per liter, MSS1 at $0.03298 per liter, and MSS2 at $0.02318 per liter.

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