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A comparative study of conventional solar stills and modified solar stills using the sound waves based agitating technique

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ABSTRACT

The demand for a suitable technique to solve the water crisis has become very challenging in the present era. Solar distillation technique using a solar still is one of the most sought techniques to produce fresh water as it is the most economical. However, the major problem is the very low productivity rate. Many have conducted experiments on solar stills, incorporating various fabrication techniques to improvise the rate of evaporation and condensation. In this research work, experimental analyses have been carried out on conventional and modified single basin, single slope solar still of the same dimensions. The modified still consists of a separate speaker unit that generates sound waves (square wave) 110 Hz and is placed under the basin. The results were compared with the conventional solar still. With the use of modified solar still, there is an increase in the contact area between the air and water molecules, which breaks boundary layer and surface tension and thereby increases evaporation efficiency. The experiments were carried out on both stills with the same atmospheric conditions. The results showed that the modified solar Still produced 61.35% more yield than the conventional still. The annual cost of distillate water made from MSS is 4.81% lower than that of CSS.

Keywords: Solar still; Sound agitated solar still; Square wave; Yield

1. Introduction

The elixir and very essence of human life on earth is water. It is well-documented that around 71% of the earth is water. The oceans, seas, and bays occupy about 97.4% of this. The freshwater sources barely constitute 2.5%. This again includes groundwater which is easily contaminated and includes water resources trapped in glaciers, icecaps, lakes, springs, rivers, and wells. So barely out of all the water bodies on earth, only around 1% is adequate for direct consumption. Presently, rapid urbanization and industrialization, along with ever increase in population, have drastically polluted and contaminated the available natural water resources to a great extent and are inadequate to satisfy the population demand. Also, contaminated water poses serious threats to humankind when consumed, and various diseases have been reported. Hence the demand for freshwater keeps increasing daily, and addressing the scarcity of potable water for domestic purposes poses a serious threat to the world. Various water distillation techniques are being investigated and incorporated to remove the saline and impure substances in water and make them suitable for consumption. Renewable energy sources play a major role next to electrical and fuel energies as they can be generated easily, are safe to use, and provide a better opportunity to meet the energy crisis. The use of a solar still, a device capable of utilizing available solar energy for water treatment, has paved the way for a cost-effective

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and easy method for distillation. Nowadays, both active and passive stills are fabricated for this purpose. Solar stills are simpler devices used to distillate brackish or impure water fabricated easily with available materials. The main drawback of using this technique is its lower productivity rates. Numerous studies are now being conducted to increase the still's production. Also, the probable enhancement of the evaporation rate and condensation occurring in the stills is primarily responsible for the increase in productivity. The productivity rate is influenced by several important factors about the basin, namely its depth, radiation-absorbing capacity, area of evaporation, cover, ability to transmit volumetric heat, thermal properties of the water in the basin, air-circulation system inside the basin, and heat loss through the bottom and side walls. When designing the basin, it is crucial to consider these criteria [1].

The investigation conducted by Taghvaei et al. [2] scrutinized the operation of active solar distillation devices in correlation with fluctuating salinity levels and aggregate solar exposure. The experiments were conducted for five consecutive days with four parallel solar stills. The stills were fabricated with different collecting areas and brine depths. The efficiency decreased in all the stills with a decrease in brine depth, and also, as the collecting area increased, the efficiency of water increased but decreased with all brine depths. The flexible, packed helical copper wires placed at the bottom of the basin act as the stretched media in a revolutionary method created by Eldalil [3] to improve the performance of the solar still. A separate resonator was also used to produce the necessary vibrations to excite the stretch media. This breaks the saline water's boundary layer and surface tension, increasing vaporization and condensation. It was reported that the productivity of using the helical coils led to 35% efficiency with an effective rate of 3.4 $L/m^2 \cdot d$ and 60% increased efficiency with 5.8 $L/m^2 \cdot d$ using the vibratory resonator technique.

The parameters of the operational efficacy of single basin double slope solar stills, which incorporate two basins of varying dimensions, were analyzed by Murugavel et al. [4]. Mild steel plates, and various heat-storage materials, including quartzite rock, red brick fragments, cement concrete fragments, and washed stone sand iron scraps, were used to construct the basins. A theoretical model was also designed and compared with actual experiment results. Using various wick materials, research was done on basin-type double-slope solar stills by Kalidasa Murugavel and Srithar [5]. In this experiment, the basin's volumetric heat capacity was reduced to increase production. Wick materials were used to construct and test the still, including light cotton cloth, sponge sheet, coir mate, and waste cotton bits in the basin. A minimal mass of water was used in the test as well. The actual values of the experimental result were compared with a theoretical model created. An energy balance equation was used to determine the temperature of the condensing glass cover, water, absorber plate, energy, and PCM medium in Ansari et al.'s [6] investigation into the desalination of salty water utilizing passive solar still with a heat energy storage system. Rajaseenivasan et al. [7] looked at potential strategies for raising multi-effect solar still production. The research entails a detailed analysis of the properties of the many stills that are now accessible. Different performance, economy, and maintenance stills were compared in great detail. Muftah et al. [8] conducted a meticulous investigation on the impact of the environment, design, and operational characteristics on the production rate of basin-type solar stills. Moreover, this study comprehensively delved into the cost analysis of the process above. Ghoneyem and Ileri [9] conducted a study to evaluate the effect of glass cover thickness on the production of stills. According to the study, a 16.5% increase in yield rate was observed using a 3 mm cover plate. The importance of the absorber plate and its modifications, the integration of condensers, and the usage of reflectors were discussed on conventional solar still. Additionally reported were the effects of humidification–dehumidification systems, incorporating thermal energy storage materials, using nanoparticles, integrating photovoltaic thermal (PV/T) modules, and thermoelectric coolers. Also, a thorough review of available solar stills and advancements in the 21st century has been discussed [10]. An experimental investigation on the solar still was carried out in Alexandria, Egypt, based on humidification–dehumidification techniques. In the research, the heated air was humidified in two stages using a heater water spatter and an ultrasonic technique, and the results obtained were discussed briefly [11]. El-Said and Abdelaziz [12] studied the efficiency of solar still while utilizing a high-frequency ultrasonic atomizer (HFU). Atomized saline water was employed in this to enhance the humidification process taking place in the SS cavity. The outcomes were briefly discussed. At various water depths, the inverted absorber solar still (IASS) and single slope solar still (SS) were the subjects of the investigation. Total dissolved solids (TDS) were considered in this case. In Muscat, Oman, the experiments are carried out. The experimental results were validated using a thermal model created for the IASS [13]. Dhivagar and Sundararaj [14] conducted an extensive analysis of many solar energy research studies, subsequently disseminating the key discoveries. It is fortunate that solar energy, which simple production processes may exploit, is used to supply the need for water.

Also, discussions and reviews were made on incorporating various methods such as fin, energy storage materials, and multi-basin solar stills for enhancing the distillate output. Many types of research focused on fins use to improvise evaporation [15]. Mevada et al. [16] considered using various fin shapes to boost a solar still's efficiency since fins might increase the water's surface area and hasten heat transfer. They also lessen the loss of bottom heat. In order to increase the production of solar still water by disturbing the water's surface in the still, an experimental study was conducted in the remote area of La Paz, BCS, Mexico. The perturbation was created by pumping air bubbles into the basin, which produced surface ripples. This caused an increase in the evaporation rate, and many outcomes were proposed [17]. Kumar et al. [18] expound upon the augmentation of production for a singular basin single slope solar still. An agitation effect and an external condenser are included in the changes. Experimental comparisons of the stills' efficacy revealed that the improved still was more efficient. The cost study demonstrated that the modification still produced a greater profit than the standard still. By expanding the water surface area and creating turbulence in the basin water, the ultrasonic fogger improves the operation of the solar still and boosts distillate production. The mist generated by the ultrasonic fogger also helps to reduce the temperature of the glass, increasing the temperature difference between the basin water and the cover and leading to increased distillate yield. The most opportune moment for utilizing the ultrasonic fogger is when the solar still experiences unobstructed solar radiation [19].

The utilization of sustainable energy sources to purify brackish or saline water to produce potable water was the subject of discussion explored by Winstor Jebakumar and Dharmalingam [20]. The experimental research focuses on the preheater-assisted productivity improvement of single-slope solar stills. The research offers insightful information on the construction and operation of solar stills for effective water production. Sivakumar et al. [21] presents an investigation of roof-type and v-type solar desalination stills, incorporating internal modifications through experimental and theoretical research. The study uses the Taguchi method to optimize freshwater production by investigating four internal modification parameters. The results show that the modified solar stills can significantly enhance productivity and have potential applications in remote and coastal areas. Reflector utilization is a low-cost improvement method for solar desalination (SD) systems. Researchers have proposed the use of dual reflectors, encompassing both internal and external mechanisms, as a viable approach to augment the efficiency of SD systems. The implementation of reflectors in the modified system leads to an elevation in both the temperature of the glass surface and the temperature of the saline water. Saline water evaporates more quickly the higher its temperature, which boosts production. According to recent research, using both interior and external reflectors can increase a still solar system's productivity by up to 40% compared to using solely internal reflectors [22]. The optimization of single-slope solar still remains linked to a solar pond that was developed by Gnanaraj and Ramachandran [23]. The Taguchi technique is used in the study to determine the amounts of four factors that perform the best. The results show that the modified solar still system can produce a significantly higher distillate yield than conventional stills. The artificial neural network concept to develop a highly accurate productivity forecast model for single slope single basin solar stills. Data from previously published articles were used to develop the model. The developed model can be applied to improve the efficiency of solar stills in real-world scenarios [24].

It is evident from the reviews carried out that there is a research gap in the use of agitation effect by sound waves generated from speakers with square waves in the bottom of the basin for the enhancement of evaporation rate and poses scope for research with improvising the productivity using sound waves agitation technique and the various parameters associated with it. In this work, the effect of sound waves on agitation efficiency is presented and compared with conventional still.

2. Experimental set-up and procedure

The experimental setup consists of two separate basin stills, one conventional type (called CSS — conventional solar still) and the other modified type (called MSS – modified solar still), to compare the productivity of solar desalination. Based on the completed literature evaluations, the stills were created. Each still's basin measured 500 by 500 mm and was constructed from 1.5 mm-thick galvanized iron sheets. An inclination angle of 30° is provided with a wall height of 100 mm on the lower side and 390 mm on the other higher side. The basins were provided with 3 mm thickness glass covers. Fig. 1a and b show the schematic arrangement and various dimensions of the fabricated CSS and MSS.

To enhance the rate of absorption, the stills were coated with black paints. In addition, the MSS basin still consists of a separate speaker setup under the basin plate to provide external agitation. The experimentation is carried out with external agitation to improve the evaporation rate. After experimenting with all possible frequencies to attain maximum agitation, the frequency of the agitation is set at 110 Hz with 102 decibels. The model of the speaker used is K20 Sonic with a 260 mm overall diameter maximum power of 40 W. A signal generator of range 50 Hz–2,000 kHz (Model Number: SM5060-2, Scientific Mes-Technik Private Limited) generates the required signals for the speakers. The square wave is a sound wave used for agitation; a CRO (Make:ScientificMes-Technik Private Limited) unit is used to determine the type of signals generated. A standard cathode-ray oscilloscope (CRO) is a device that accurately

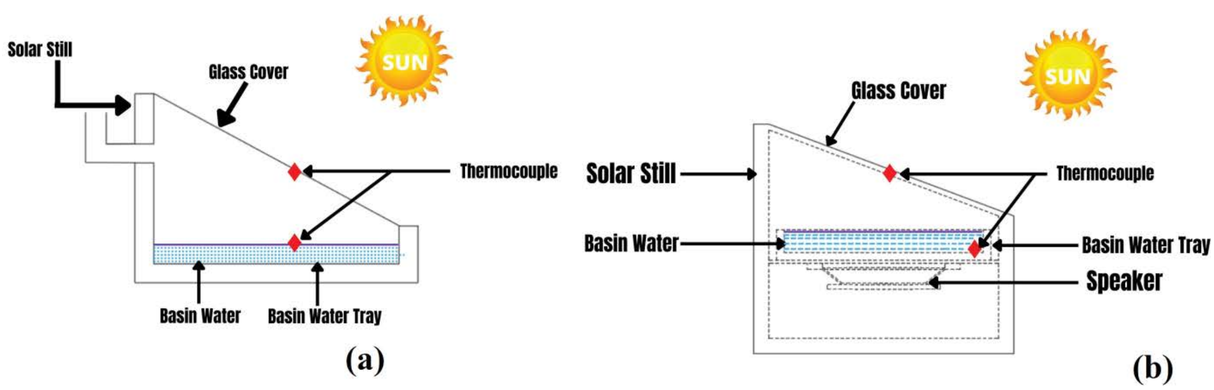

Fig. 1. (a) Conventional and (b) modified solar still.

measures the time and amplitude of signals across a wide frequency range—attached next to the signal generator. A Ramco brand amplifier (IC 4440) is connected to the CRO output, which is used to amplify the signal produced and is finally connected to the speaker. The sound agitation of the single slope single basin solar still, as shown in Fig. 2.

Fig. 3 shows a schematic arrangement of the modified basin still. A 1 cm water depth is maintained in both the solar stills. The stills were placed at 10.9598°N and 76.8995°E longitude in Pachapalayam, Coimbatore, with the same atmospheric conditions to note the exact improvements in their performance efficiency. The measurements, such as solar radiation, atmospheric temperature, basin temperature, water temperature, and glass temperature, were taken every 1-h duration throughout the day from 6.30 am to 6.30 pm. Different measuring instruments, such as solar power meters, thermometers, and thermocouples, were used to obtain the necessary readings. The various inferences obtained are discussed briefly in the results and discussion parts. Fig. 4 shows the actual experimental setup.

2.1. Error analysis

The analysis of errors in experimental physical measurements is known as error analysis. In order to calculate the percentage errors associated with measuring instruments such as thermocouples, temperature indicators, solarimeters, and distillate measuring jars, Velmurugan et al. [25] presented the following formula.

$$\text{Error} = \frac{\text{Accuracy of the minimum instrument}}{\text{value of the output measured}} \times 100\% \quad (1)$$

Fig. 2. Surface pattern on the basin water surface due to square type sound wave vibrations.

Table 1 provides information on the accuracy, range, and error percentage for several measuring devices utilized in experiments.

3. Results and discussions

The experiments were conducted on sunny days in March 2020 between 6.30 am to 6.30 pm using the square wave agitation technique and compared with the conventional type. Fig. 5 depicts wind velocity and the respective solar insolation for the stipulated periods for both stills. The results show that solar insolation value reaches a maximum value of 1,115 W/m^2 around 13.30 pm. and decreases gradually. It is due to the presence of abundant solar energy. This happens mutually for both the stills. As the solar intensity reaches a maximum value, the ambient temperature also reaches its maximum value during the peak hours of the day. Wind velocity (m/s) consistently rises and falls at regular intervals.

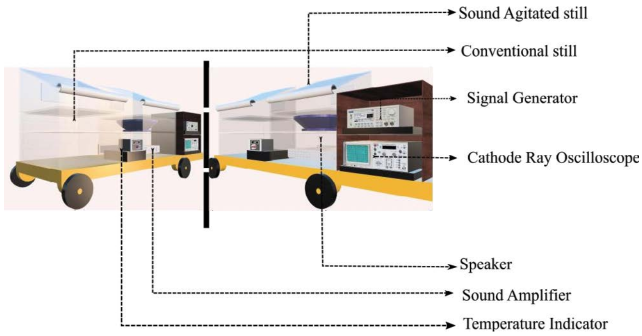

Fig. 3. Experimental setups of conventional and modified stills - schematic representation.

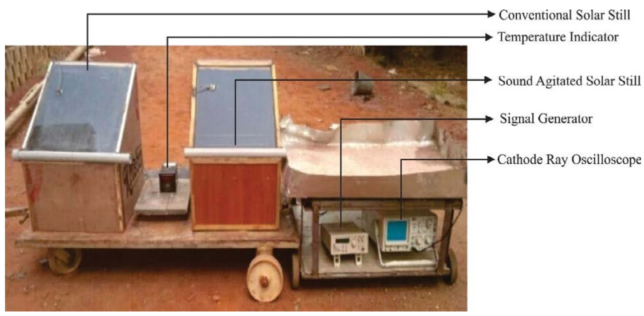

Fig. 4. Actual experimental set-up.

Table 1
Accuracy, range, and percentage error of the measuring instruments

Instrument	Accuracy	Range	Least value measured	Percentage error
Solar power meter	±1 W/m^2	0–3,999 W/m^2	10	10
Measuring jar	±1 mL	0°C–1,000 mL	10	10
Thermometer	+1°C	0°C–100°C	23.9	4.184
Thermocouple	0.1°C	0°C–150°C	25	0.4
Temperature indicator	0.1°C	0°C–300°C	25	0.4

Fig. 6 compares various temperatures over time for traditional solar still. The stills' ambient temperature rises in direct proportion to the strength of the sun's rays, peaking at midday. For both stills, the surrounding temperature is constant. At 13.30 pm, the traditional solar still's maximum basin temperature of 72°C is reached. The surface water temperature of conventional solar still is, most of the time, higher than the basin temperature. Because solar radiation first falls on the glass and then falls on the basin water, due to its enormous heat capacity, it takes longer to heat up. The maximum surface water temperature of conventional solar still is 72.7°C at 13.30 pm. After 9.30 am, the glass cover's temperature is lower than the basin's and the water's surface temperatures. The average difference between ambient temperature and condensate temperature is 3.2°C.

Fig. 7 shows the graph depicting the square wave experimentation for the agitation of water in the modified stills. The graphs show the temperature of the basin, the surface water, the glass cover, and the condensate, all in °C, plotted against various time intervals in hours. The maximum basin temperature attained in the modified solar still is 76°C at 13.30 pm. The maximum surface water temperature of modified solar still is 76.7°C at 13.30 pm. The average difference between ambient temperature and condensate temperature is 2.8°C.

From the graph in Fig. 8, from 6.30 am to 9.30 am surface water temperature of both stills are same, even if the modified solar is still agitated. From 10.30 am to 16.30 pm, MSS leads over CSS. Between 10.30 am and 16.30 pm, there is an average surface water temperature differential of 2°C between

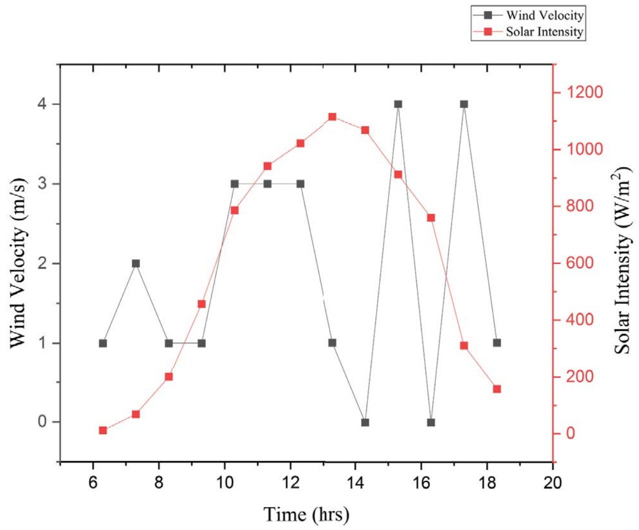

Fig. 5. Wind velocity and solar intensity variation throughout the experiment for both conventional and modified solar still.

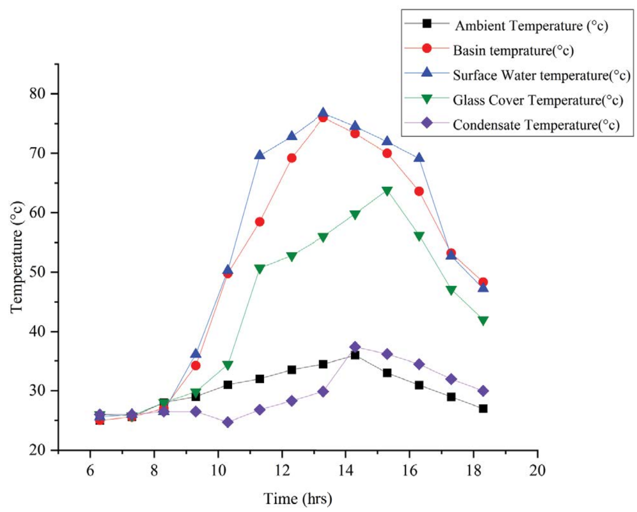

Fig. 7. Comparison of different temperatures with time for modified solar still.

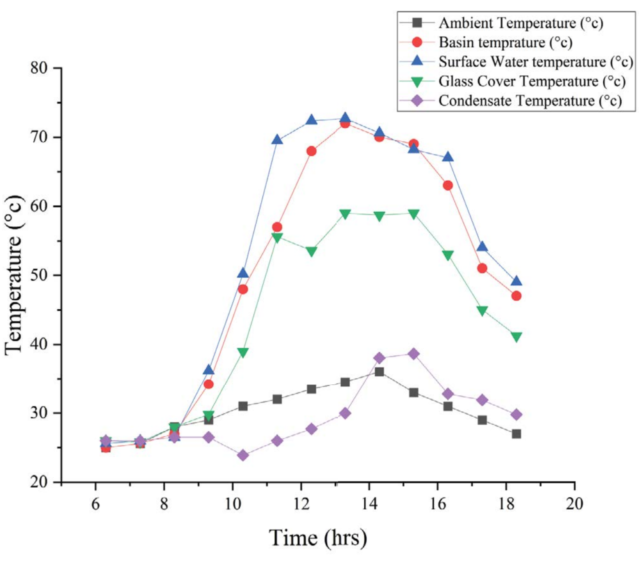

Fig. 6. Comparison of different temperatures with time for conventional solar still.

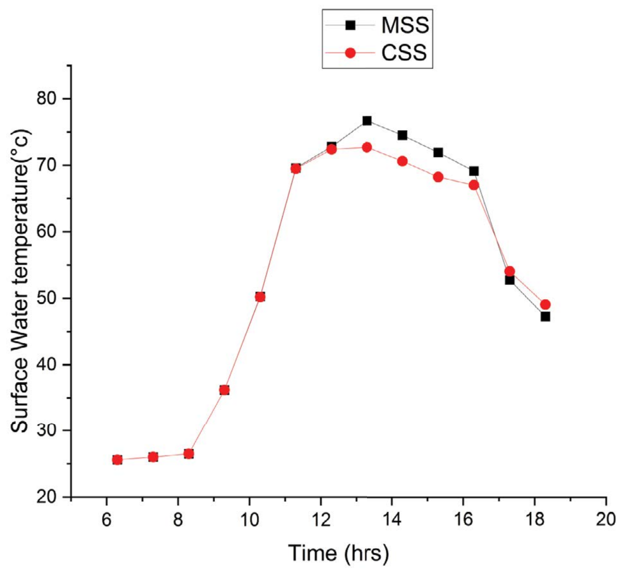

Fig. 8. Comparison of surface water temperatures with time for conventional and modified solar still.

the MSS and CSS. The sound waves that constantly agitated the water from the beginning of the experiment until its conclusion are to blame for this greater figure of surface water temperature [19]. Wakes on the surface, emanating from the sound wave in all directions, can be observed in Fig. 2.

Fig. 9's graph displays the MSS and CSS's glass cover temperature. Due to the vibration effect in the MSS, the mist is produced in the glass cover of the modified solar still. As a result, the glass cover temperature of the CSS leads over the MSS most of the time. MSS's temperature difference (Tw-Tg) always leads to that of CSS. Due to this, the modified solar yield is still high [26].

Fig. 10 shows that the MSS's basin water temperature is greater than the CSS's basin water temperature. The average basin Temperature of MSS and CSS is 52°C and 51°C. At the start of the experiment basin water temperature of both CSS and MSS will be the same. After 10.30 am, the MSS basin water temperature leads over CSS. At 1.30 pm basin temperature of MSS leads CSS by 5.5%.

Fig. 11 shows the productivity of the stills. The graph shows the yields obtained for both the conventional and modified (square wave type) stills. At 18.30 h, the modified still type produced a maximum production of 405 mL, whereas the standard still type concurrently produced a yield of 251 mL. The results obtained show that the modified solar still with square wave agitation produces good yield results. Enhanced sound waves and increased incidence of solar radiation result in a higher overall distillate yield of 61.4%.

3.1. Thermal efficiency

The relationship between the solar still's output and efficiency [18]:

$$\eta = \frac{M'_w \times L_{ev}}{A_b \times \sum I(t) \times \Delta t} \quad (2)$$

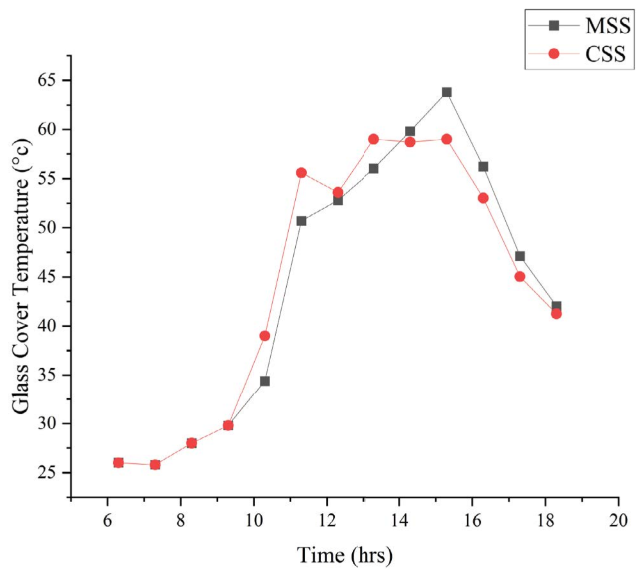

Fig. 9. Comparison of glass cover temperatures with time for conventional and modified solar still.

where $M'w$ is daily distillate output per unit basin area (kg/m²·d); L_{ev} is the latent heat of the vaporization of water (J/kg); A_b is the basin surface area of still (m²); $I(t)$ is solar intensity (W/m²), t is time interval (s).

Conventional and modified solar thermal efficiency was 36.27% and 58.52%, respectively. From this, it concluded that the modified solar still has 22.25% higher efficiency than the conventional solar still.

3.2. Cost analysis

The following steps should be followed to determine the cost per liter (CPL) of distilled water: Taking into account the cost of manufacturing and installing the solar sill as P

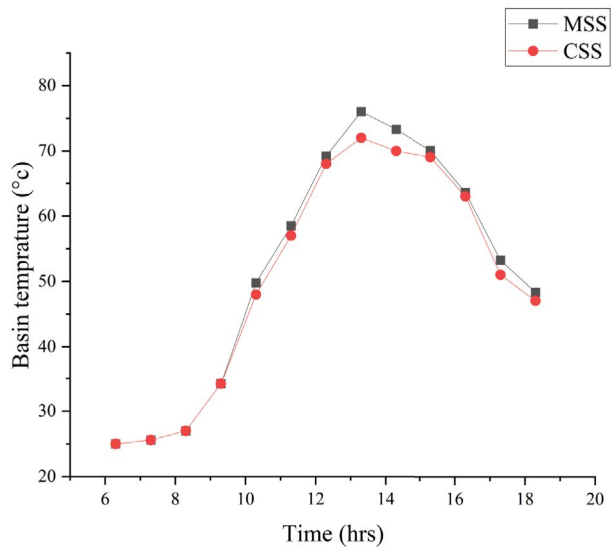

Fig. 10. Comparison of basin temperatures with time for conventional and modified solar still.

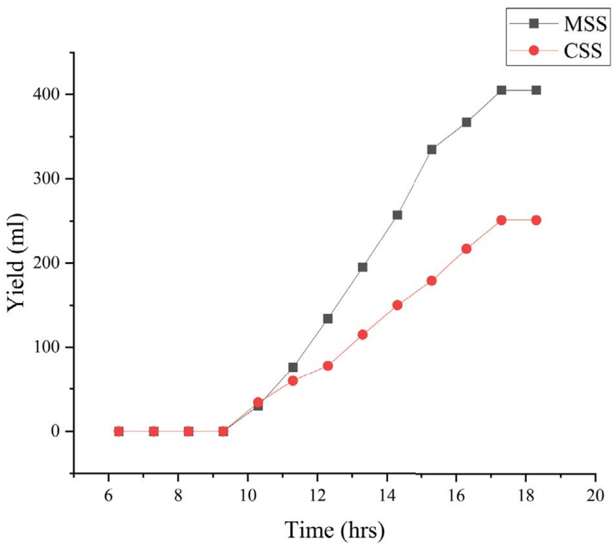

Fig. 11. Comparison of the productivity of conventional solar still and modified solar still.

Table 2
Installation cost and salvage value of different components of CSS and MSS (in US $)

	CSS	MSS	S*
Installation cost and salvage value of different components of CSS and MSS (in Rs.)			
FRP solar still	60.90	60.90	6.1
Glass	4.87	4.87	
Putty	3.65	3.65	
Tubing	0.18	0.18	
Speaker with amplifier		37.14	37.14
Total cost	69.61	106.75	

Table 3
Values of different costs and factors for CSS and MSS

	CSS	MSS
CRF	0.1468	0.1468
SFF	0.0268	0.0268
FAC	839.1005	1,286.7676
ASV	13.4121	21.5908
AMC	125.8650	193.0151
AC	951.5534	1,458.1919
AY	495.04	797.014
CPL	1.9221	1.8295

Table 4
Comparison of similar research work

Research work	Yield improved %
Kumar et al. [18], solar still using agitation effect and external condenser	39.5
Dumka and Mishra [19], solar still augmented with the ultrasonic fogger	33.3
Productivity comparison of conventional and square wave sound agitation (modified)	61.4

and an interest rate of i (i is set at 12% for the purposes of the analysis). For a system with an n-year lifespan, the capital recovery factor (CRF) and sinking fund factor (SFF) may be computed as follows [19]:

$$\text{CRF} = \frac{i\left(i+1\right)^{n'}}{\left(i+1\right)^{n'}-1} \tag{3}$$

$$\text{SFF} = \frac{i}{\left(i+1\right)^{n'}-1} \tag{4}$$

Using the relationships indicated above, the annual salvage value (ASV) and first annual cost (FAC) will be calculated:

$$\text{FAC} = \text{CRF} \times P \tag{5}$$

$$\text{ASV} = \text{SFF} \times S \tag{6}$$

where S (which is equal to 50% of the initial cost) is the distiller unit's salvage value when it has reached the end of its useful life. The expense necessary to keep the still running throughout the year is known as the annual maintenance cost (AMC). 15% of the FAC is thought to be made up of AMC. The annual cost (AC) after that will be:

$$\text{AC} = \text{FAC} + \text{AMC} - \text{ASV} \tag{7}$$

Hence, the CPL can be written as:

$$\text{CPL} = \frac{\text{AC}}{\text{AY}} \tag{8}$$

where AY is the annual yield from the solar still.

Table 2 displays the cost breakdown of the various parts that CSS and MSS are made up of, as well as their salvage value after 15 years. The values of various parameters and costs for CSS and MSS are shown in Table 3. As a result, the annual cost of distillate water made from MSS is 4.81% lower than that of CSS. So, from both an economic and distillate output standpoint, enhancing sound agitation with CSS during peak radiation hours is a better approach.

3.3. Comparative study of the still with similar skill

Table 4 represents the improved efficiency of different research and present research.

4. Conclusion

Conventional and modified type solar stills were fabricated to the same dimensions. The modified still was provided with external speakers to achieve an agitation effect on the basin water and to improve the evaporation rate. A square sound wave format is utilized for this purpose using a signal generator at a frequency of 110Hz. A comparative study was carried out to determine the performance augmentations between the conventional still and square waves generated. It was determined that the yield of the modified solar still with the square wave technique provides a maximum yield of 61.35% more than the conventional still. Hence the modified still with the square wave technique can be utilized for various applications. The use of sound wave techniques in solar stills paves the way for much research to be carried out as it contains many parameters of interest. Also, the cost and energy considered for the modifications are very nominal. This particular area has many research gaps that are to be tapped into, and also, by the mere modification and controlling of the various parameters available in this technique, maximum efficiency can be produced in a much more viable and economical way.

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