International Journal of Science and Research (IJSR)
ISSN: 2319-7064
SJIF (2022): 7.942

Experimental Investigation on the Performance Enhancement of Conventional Solar Still by Using Nano Particles, Wick and Gravels Integrated with Condenser Cooling

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Abstract: ***Solar still is generally used for extraction of salt and purification of brackish water for drinking, agricultural and industrial purposes. Less volume of distillation output from solar still is a serious concern. Hence, an experimental setup is manufactured and fabricated for the same. Objective is to increase the evaporation and condensation in solar still by using nano particles, wick and gravels integrated with condenser cooling. To enhance the evaporation in single slope solar still, the combinations of nanoparticles, gravel and black wick are used in the still basin. For condensation improvement, the still in connected with a horizontal tubular air cooled aluminium condenser. In the experiment, temperature at basin, temperature at inner glass surface and distillation output are measured for three cases namely, Case - 1: Comparison between Conventional Solar Still and Revised Solar still having gravels immersed in basin Case - 2: Comparison between Conventional Solar Still and Revised Solar still having gravels immersed in basin and covered with black wick and Case - 3: Comparison between Conventional Solar Still and Revised Solar still having gravels immersed in aluminium oxide nano fluid (1% wt concentration in the saline water) in the basin and covered with black wick. The experimentally measured results of revised solar still is compared with the results using conventional solar still to assess the enhancement. The maximum basin water temperature achieved for revised solar still in Case - 1, Case - 2 and Case - 3 are 62.3 °C, 57.9 °C and 61.7 °C respectively. The maximum cumulative distillate output for revised solar still in Case - 1, Case - 2 and Case - 3 are 0.87 liters, 0.88 liters and 0.93 liters respectively. For Case - 1, Case - 2 and Case - 3, revised solar still gave a total of 42.63%, 46.67% and 47.62 % higher distillate output than conventional solar still.***

Keywords: Solar desalination, Distillation output, Nano particles, Gravels, Wick, Condenser cooling

1. Introduction

Water is uninhibitedly accessible normal asset on the earth. Over 70% of the World's region is covered by water however exceptionally less measure of water is accessible for direct human utilization. Around 97% of the water on earth is in sea, roughly 2% of the water is put away as ice in polar district and just 1% of complete water is accessible for the need of people, plants and creatures which is as streams, lakes and underground repositories [1]. As per the World Health Organization (WHO), the acceptable threshold for salinity in water is 500 parts per million (ppm), whereas seawater typically contains salinity levels ranging from 35, 000 to 45, 000 ppm in the form of total dissolved solids. The objective of a desalination system is to purify brackish or seawater, ensuring that the water supplied contains total solids below the permissible limit of 500 ppm. Consequently, utilizing desalination for addressing water scarcity becomes an appealing option. Significant innovative work endeavors have been committed to researching feasible and practical methodologies for producing consumable water utilizing sustainable power sources. Among these, bridling sunlight based energy for water desalination stands apart as the most encouraging and savvy strategy for providing clean drinking water to far off regions. Solar stills offer numerous benefits, including affordability, straightforward assembly, and minimal upkeep. However, they suffer from a notable drawback: reduced efficiency and limited production of drinkable water. Both experimental and theoretical endeavors have been undertaken to bolster solar still efficiency. Shahin Shoeibi et al. [2] review in detail to assess the impact of employing diverse methods simultaneously to enhance solar still performance. To achieve this objective, several techniques for increasing water temperature were explored, including nanoparticles, phase change materials (PCM), thermoelectric heating, photovoltaic/thermal systems, solar collectors, air heaters, and electrical heaters. Furthermore, methods aimed at reducing the temperature of the condensation area, such as glass cooling, external condensers, and thermoelectric cooling, were examined. Mohamed Salem et al. [3], experimentally studies the influence of integrating a floating sponge layer on the performance of a solar still distillation unit. Utilizing a floating sponge with a density of 16 kg/m^3 and thickness of 30 mm, at a saline water depth of 10 mm, achieves maximum freshwater production of 4.9 L/m^2 per day and thermal efficiency of 37%, marking a +58.1% and +55.3% increase, respectively, compared to the conventional unit's performance (3.1 L/m² per day freshwater productivity and 23.8% thermal efficiency). W. M. Alaian et al. [4] experimentally investigated the performance of Solar still augmented with pin - finned wick evaporation surface. The use of a pin - finned wick enhances both the productivity and efficiency of the still. This improvement results in a system productivity increase of over 23%. A. E. Kabeel et al. [5] experimentally examined the impact of various types of nanomaterials on solar still performance, specifically focusing on cuprous and aluminium oxides as solid nanoparticles. The utilization of aluminium oxide nanoparticles resulted in a 125.0% increase in distillate yield with the fan and an 88.97% increase without it, in comparison to the conventional still. S. W. Sharshir et al. [6] experimentally investigated the use of graphite and copper oxide micro - flakes with different concentrations, different basin water depths, and different film cooling flow rates in an attempt to improve the performance of solar still. The most significant increase in modified still productivity is observed with graphite micro - flakes, with enhancements of 53.95% and 43.10% recorded with and without glass cooling during daytime operations at a brine water depth of 0.5 cm and a concentration of 1%. H. Sharon et al. [7] conducted the experiments on tilted solar still with basin and tilted solar still with wick in the basin to assess their performance, distillate quality, environmental benefits and economic feasibility. During experimentation, the tilted solar still with basin and wick achieved maximum distillate yields of 4.48 L/d and 4.62 L/d, respectively, with corresponding cumulative solar radiation levels. A. S. Abdullah et al. [8] examined the effects of internal reflectors on the performance of tray distillers. The trays solar still exhibited enhanced evaporation and condensation rates when nanoparticles were utilized, leading to improved heat transfer characteristics and water temperature compared to the reference solar still. Manoj Dubey et al. [9] experimentally and theoretically analysed conventional and modified single basin still with double slope augmented with black dye, pebbles and iron chips. In Modified Double Slop Solar still compared to Conventional Solar Still, there's a significant 28.4% increase in distillate output and a noteworthy improvement of 25.01% in overall thermal efficiency. Pankaj Dumka et al. [10] evaluated the performance of single slope solar still augmented with sand filled bags. The addition of sandbags to a conventional solar still (CSS) has been shown to enhance both distillate output and efficiency. Specifically, there has been an improvement of 28.56% and 30.99% in cumulative distillate yield for basin water quantities of 30 kg and 40 kg, respectively, when the solar still is augmented with sandbags. A. E. Kabeel et al. [11] presented a detailed review of the different solar stills integrated with different condensers arrangements The condensers with solar stills can be divided into three types; built - in condensers, external condensers, and internal condensers. Saleh Abo - Elfadl et al. [12] experimentally investigated the efficacy of various passive condenser designs in solar distillation, considering productivity, exergy, energy, energy - economic, exergy - economic, and enviro - economic factors. Husham M. Ahmed et al. [13] conducted experiments to evaluate the impact of integrating built - in passive condensers with traditional single slope basin solar stills. Incorporating a built - in condenser into the conventional solar still led to a 16.7% increase in productivity compared to the standard configuration without a condenser. After carrying out the detailed literature review, it is found that most of the research work is done to enhance the distillate output of the still by modifying the design of the basin or by addition of heat absorbing and phase changing materials for faster evaporation or by addition of cooling devices for faster condensation. It has been found that very less attention is given to enhance evaporation and condensation simultaneously. It is essential to invest cost effective methods for improving evaporation and condensation simultaneously in the solar still. Addition of different combination of aluminium oxide nano particle, wick and gravels to the basin of the conventional solar still with integration of a horizontal tubular air cooled aluminium external condenser are not yet experimentally investigated.

2. Experimental Setup

2.1 Model Design and Fabrication

For comparative study of distillate yield of solar stills, two solar still, namely, conventional solar still and revised solar still are designed and fabricated as shown in Figure 1 & 2. Both stills are manufactured from mild steel sheet of 2 mm thickness. Basin of both solar stills have same configuration. The area of basin is 0.25 m^2 (0.5 m × 0.5 m). The height of low side wall is kept 0.2 m and high side wall is kept 0.42 m. The whole basin surfaces are painted with black paint from inside to absorb the maximum solar radiation incident upon it. A hole of diameter 18 mm is drilled on lower side of the basin wall to provide inlet water connection using flexible hose pipe from water tank to the basin. An another hole of 15 mm is drilled on upper side of the basin wall to provide outlet connection of condensed water vapour from still to collection flask. In revised solar still, two additional holes of 53 mm diameter are drilled on higher side wall to connect external condenser pipes to the basin. The basin is covered with a transparent glass sheet measuring 0.5 m × 0.52 m with a thickness of 3.5 mm. Positioned at an angle of 23° with respect to the horizontal; the glass cover is securely sealed with silicone to prevent any vapour leakage from the still. The exterior surfaces of the basin are insulated with a layer of foam insulation measuring one inch in thickness. In revised solar still, an external horizontal tubular condenser is attached to the basin. The condenser is constructed of two parallel aluminium tubes measuring 305 mm in length, 50 mm in outer diameter, and 1.5 mm in thickness per tube, aluminium is chosen for its high conductivity and light weight properties. To aid in the drainage of condensate water, a slight 5° incline is incorporated into the condenser tubes. Shielding the condenser from solar radiation, a cardboard sun - shade cover is positioned above it, spaced at 40 cm above from the top surface of the still to allow for ambient air circulation around the tubes. U - PVC tubes (each 50 mm in diameter) with pipe fittings establish the connection between the still and condenser. The distance between the condenser and still is 75 cm (measured from center to center).

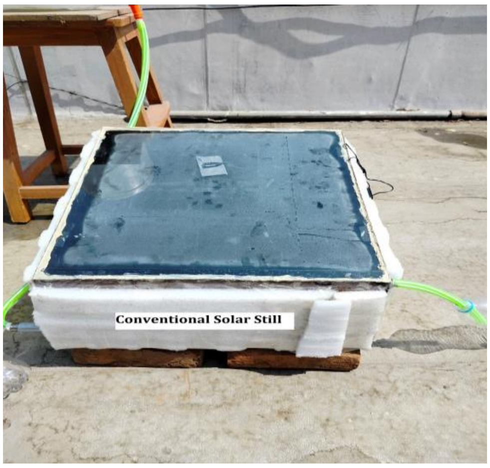


Figure 1: Conventional Solar Still

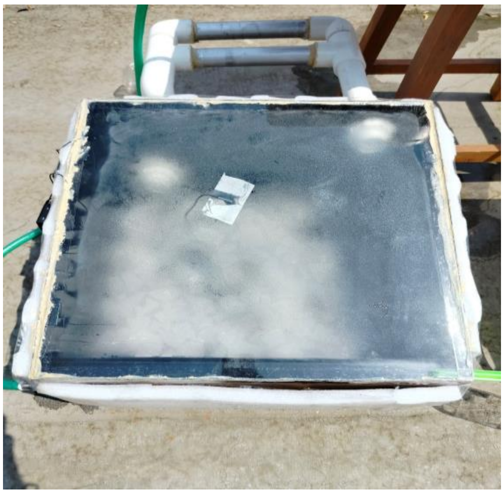


Figure 2: Revised Solar Still

Condensate water from the top of the glass is collected in the distillate trough due to the slanting of the glass cover. In the present experimental setup, distillate trough having dimensions (0.5 m × 0.06 m × 0.03 m) is placed at top of the lower side wall to collect condensate water from the glass cover. A feed water drum of capacity 20 litre is used to supply saline water to the basins of both solar stills. Two outlet connections with flow control valves are provided at the bottom of the tank.

3. Experimental Procedure

In the present experiment work, Conventional Solar still and Revised Solar still are tested under the same conditions in the month of February and March 2024 during clear sky days. The experimental setup was installed at the terrace of my college - Dr. Jivraj Mehta Institute of Technology, Mogar, Anand, Gujarat, India as shown in Figure 3. Both Solar stills are placed facing south direction to receive maximum solar radiation through all time. The latitude angle of Anand city is 22.3299° N – 72.6151° E and glass cover of both solar stills are inclined at 23° angle matching with the latitude angle of Anand city [14]. During the procedure of current experimental work, following three cases are tested:

Case - I: Comparison between Conventional Solar Still and Revised Solar still having gravels immersed in basin (in February, 2024) (Figure 4)

Case - II: Comparison between Conventional Solar Still and Revised Solar still having gravels immersed in basin and covered with black wick (in February, 2024) (Figure 5)

Case - III: Comparison between Conventional Solar Still and Revised Solar still having gravels immersed in Aluminium oxide nano fluid (1% wt concentration in the saline water) in the basin and covered with black wick (in March, 2024) (Figure 6)

Figure 3: Experimental Setup

Figure 4: Photo of Revised Solar still basin with gravels (Case-I)

Figure 5: Photo of Revised Solar still basin with gravels covered by black wick (Case-II)

Figure 6: Photo of Revised Solar still having gravels immersed in Aluminium oxide nano fluid (1% wt concentration in the saline water) in the basin and covered with black wick (Case-III)

The basin areas of both solar still was filled with saline water. To simulate the sea water, 700 g of salt was dissolved in 20 litre of tap water (35 g/litre) and the saline water was stored in the Feed water drum. Inside the basin areas, markings are done at the height of 20 mm to maintained

Paper ID: SR24516234737 DOI: https://dx.doi.org/10.21275/SR24516234737

water level at constant height of 20 mm in both solar stills. Feed water drum was connected to both solar still basins through flexible hose pipe. The water inside the basin of solar still receives the solar radiation and gets evaporated. Due to incorporation of gravels, black wick and Al_2O_3 Nano Powder, the heat transfer coefficient of basin water increased [15], generating more heat inside the still. From the generated heat inside the solar, some portion of vapour moves the upper side and fixes on the glass cover's inner surface, where it condenses. The remaining vapour moves towards the condenser area. In the condenser, surface areas of aluminium tubes give extra space to expand the vapour. Due to atmospheric air contact with the external surface of aluminium tubes air cooled condenser condenses the vapour inside it and provides distillate water. The condensed water from the condenser was also collected to the separate flask through the pipe attached to the bottom of the condenser area.

Figure 7: Aluminium Oxide Nano Powder (25gm) and Black Cotton Wick used in the experiment

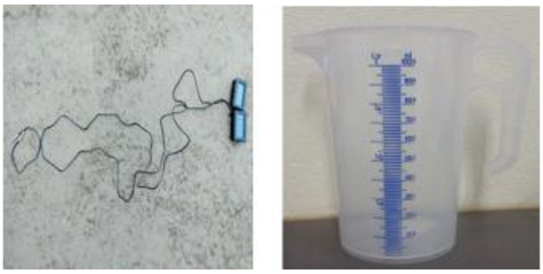
Table 1: Properties of materials used in the basin of revised solar still

Sr. No.	*Materials*	*Thermal Conductivity*
1	Gravels (Marble stone)	2.94 W/m K
2	Black cotton wick	0.026 - 0.065 W/m K
3	Al2O3 Nano Powder (20 - 50 nm)	20 - 30 W/m K [14]

The experimental readings were taken from Morning 9: 30 a. m to the evening 4: 30 p. m (7 hours) in the month of February, 2024 and March, 2024. In experimental reading, temperature of basin water (T_{bw}), inner glass cover temperature (T_{gi}), ambient temperature (T_a), hourly distillate output and cumulative distillate output were measured in all experimental days. To measure different temperature parameters like; inner glass cover (T_{gi}), basin water (T_{bw}), and ambient temperature (T_a), a total of five thermocouples were located in two different solar stills. Among that, five thermocouples measure the basin and glass temperatures of two different solar still, and one thermocouple measures the ambient temperature. All temperature readings during the experimental day were noted in the notebook. A graduated plastic measuring jar was used for measuring distilled water per hour. The graduated plastic measuring jar was having capacity of 1000 ml with least count of 10 ml. In Table 2 instruments used during experimental work, its accuracy and range are shown.

Table 2: Instruments used during experimental work

Sr. No.	*Instruments*	*Range*	*Accuracy*
1	Thermocouple	- 50°C to 110°C	+ 1°C
2	Measuring Jar	0 - 1000 ml	±10 ml



(a) (b)

Figure 8: Instruments used in experimental work (a) RTD Thermocouple (b) Measuring Jar

4. Results and Discussion

The experimental results of case - I, case - II & case - III were compared with results of conventional solar still. The different parameters like basin water temperature (T_{bw}), inner glass cover temperature (T_{gi}), ambient temperature (T_a), hourly distillate output, and cumulative distillate output were measured.

4.1 Comparison between Conventional Solar Still and Revised Solar still having gravels immersed in basin (on 15th February, 2024)

A higher temperature of the water in the basin results in an increased rate of evaporation within the solar still, thereby enhancing its efficiency [15]. Figure 9 illustrates the fluctuation of basin water temperature with atmospheric temperature for both the conventional solar still and the Revised Solar Still incorporating gravel in the basin. The basin water temperature consistently remains higher in the Revised Solar Still with gravel compared to the conventional solar still. This heightened water temperature in the Revised Solar Still can be attributed to the inclusion of gravel (marble stones), which absorbs more solar radiation, elevating the temperature within the basin and facilitating faster evaporation of water.

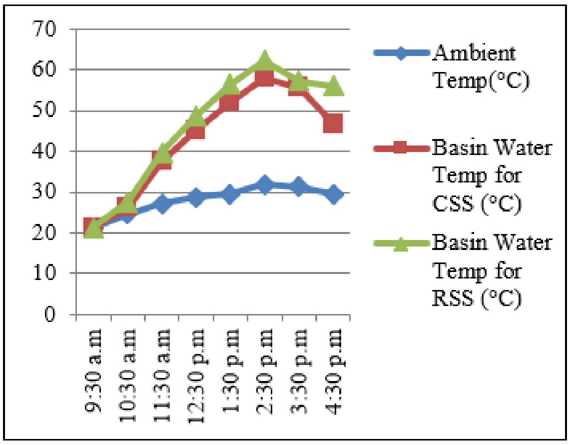


Figure 9: Hourly variation of basin water temperature with ambient temperature (15 - 02 - 2024)

A narrower temperature gap between the water and the glass cover enhances the productivity of the solar still. Figure 10 illustrates the hourly fluctuations of the inner glass cover temperature for both the conventional solar still and the Revised Solar still with gravel immersed in the basin. The inner glass cover temperature is also influenced by ambient

Paper ID: SR24516234737 DOI: https://dx.doi.org/10.21275/SR24516234737

temperature. At 2: 30 p. m., the maximum inner glass cover temperature recorded for the conventional and Revised Solar stills with gravel immersed in the basin were 54.1°C and 57°C, respectively. The inner glass cover temperature for both types of solar still remained almost identical because of a horizontal tubular air - cooled condenser to the Revised Solar still.

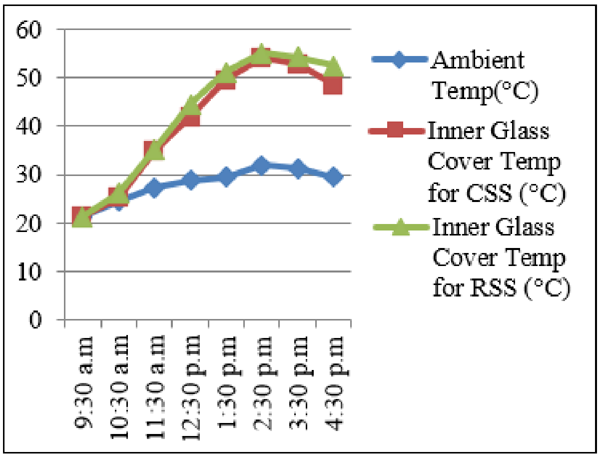


Figure 10: Hourly variation of Inner Glass Cover temperature with ambient temperature (15 - 02 - 2024)

In Figure 11, a comparison of the hourly distillate output between the conventional and revised solar still is presented. Initially, during the first hour of the experiment, there was minimal disparity in distillate production between the two solar stills. However, between 12: 30 p. m. and 4: 30 p. m., a notable difference in distillate output emerged between the two setups. Compared to the conventional solar still, the revised version consistently exhibited a superior distillate output. This improvement in distillate output in the revised solar still can be attributed to two main factors: the incorporation of a horizontal aluminium tube air - cooled condenser and the addition of gravel (marble stones) into the basin.

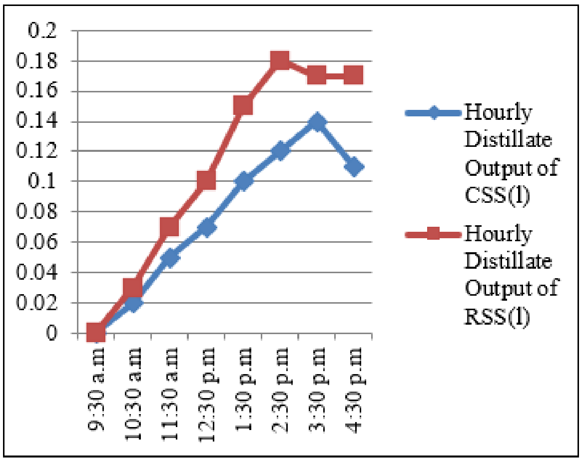


Figure 11: Hourly variation of distillate output with time (15 - 02 - 2024)

In figure 12, a comparison in cumulative distillate output between conventional and revised solar still is shown. It can be seen from the figure that the graph of distillate is continuously increasing with time. The revised solar still gave a total of 42.63 % of higher distillate output than conventional solar still.

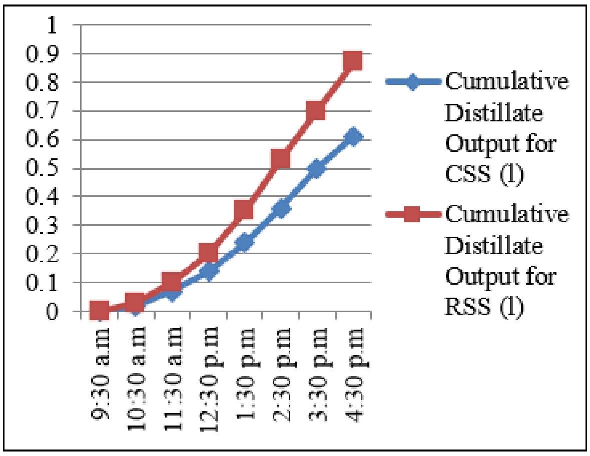


Figure 12: Hourly variation of cumulative distillate output with time (15 - 02 - 2024)

4.2 Comparison between Conventional Solar Still and Revised Solar still having gravels immersed in basin and covered with black wick (on 26th February, 2024)

Research findings suggest that expanding the surface area of the basin can positively influence the distillate yield of solar stills by improving the rate of heat transfer between saline water and absorbent surfaces. The utilization of wick material in solar stills enlarges the exposed wet area to the solar absorber, presenting a promising avenue for increasing the evaporation rate of solar stills through direct heat transfer to the saline water. Here in figure 13, a variation of basin water temperature with atmospheric temperature between conventional solar still and Revised Solar still having gravels immersed in basin and covered with black cotton wick is shown. The maximum values of basin water temperature obtained at 2: 30 p. m. for conventional solar still and Revised Solar still having gravels immersed in basin were 54.5 °C and 57.9 °C, respectively.

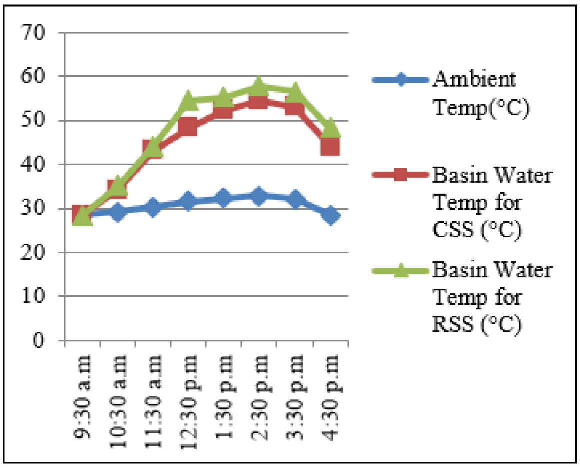


Figure 13: Hourly variation of basin water temperature with ambient temperature (26 - 02 - 2024)

In figure 14, the hourly variation of inner glass cover temperature for conventional solar still and Revised Solar still having gravels immersed in basin and covered with black cotton wick is shown. The maximum value of inner glass cover temperature at 2: 30 p. m. for conventional Solar still was 52.5 °C and for Revised Solar still having gravels immersed in basin and covered with black cotton wick was 52.2 °C. The attachment of a horizontal tubular air - cooled condenser maintained the difference of temperature between water and glass cover and increased the distillate output of solar still.

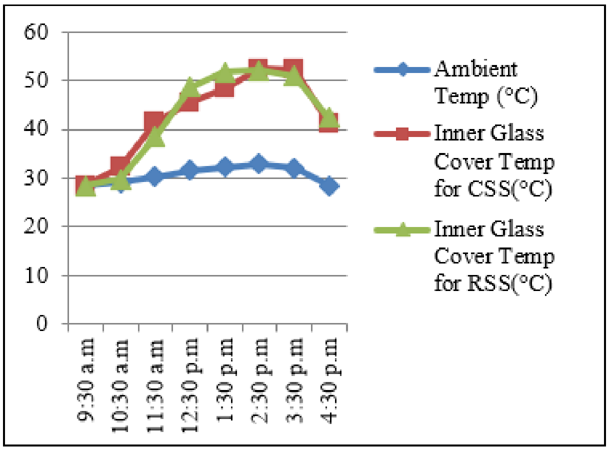


Figure 14: Hourly variation of Inner Glass Cover temperature with ambient temperature (26 - 02 - 2024)

From figure 15, the highest hourly distillate obtained at 1: 30 p. m. for conventional solar still was 0.13 l and at 2: 30 p. m. for revised solar still was 0.17 l, respectively. Gravels with wick increases the subjected wet area to absorb more amount of solar radiation and increase the temperature within the basin, thereby promoting faster evaporation of water; hence higher distillate could be achieved. From figure 16, the total distillate output obtained for the conventional and revised solar stills was 0.60 liters and 0.88 liters, respectively. By incorporating a horizontal aluminium tube air - cooled condenser, adding gravel (marble stones) to the basin, and covering it with black cotton wick in the revised solar still, a higher distillate yield could be achieved compared to the conventional solar still. The revised solar still yielded a total of 46.67% more distillate output than the conventional solar still.

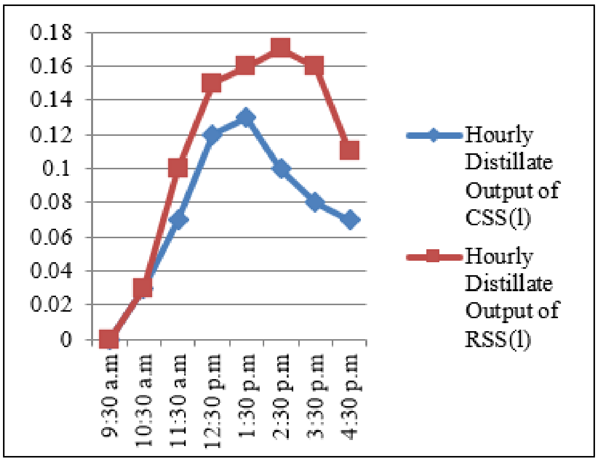


Figure 15: Hourly variation of distillate output with time (26 - 02 - 2024)

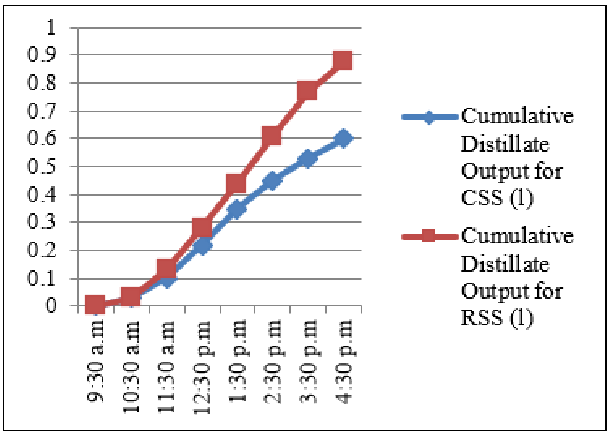


Figure 16: Hourly variation of cumulative distillate output with time (26 - 02 - 2024)

4.3 Comparison between Conventional Solar Still and Revised Solar still having gravels immersed in Aluminium oxide nano fluid (1% wt concentration in the saline water) in the basin and covered with black wick (on 11th March, 2024)

It has been found that very less attention is given to enhance evaporation and condensation simultaneously. For evaporation enhancement, three combinations were applied in the still basin, which consisted of Aluminium oxide nano fluid (1% wt concentration in the saline water), black cotton wick and gravels (marble stones) materials. Nano fluid means mixing the base fluid with solid - sized nanoparticles. The suspended nanoparticles change the heat transfer characteristics and evaporative rate of the base fluid. In this experimental work, i. e. in Case - 3, Conventional Solar Still and Revised Solar still having gravels immersed in Aluminium oxide nano fluid (1% wt concentration in the saline water) in the basin and covered with black wick are experimentally tested on the same conditions. Figure 17 displays the fluctuation of basin water temperature concerning ambient temperature in both the conventional solar still and the Revised Solar still, which incorporates gravel immersed in aluminium oxide nano - fluid (at 1% weight concentration in saline water) within the basin, covered with black wick. At 12: 30 p. m., the conventional solar still recorded a maximum basin water temperature of 53.5°C, while the Revised Solar still, with gravel immersed in aluminium oxide nano - fluid and covered with black wick, reached 61.7°C at the same time.

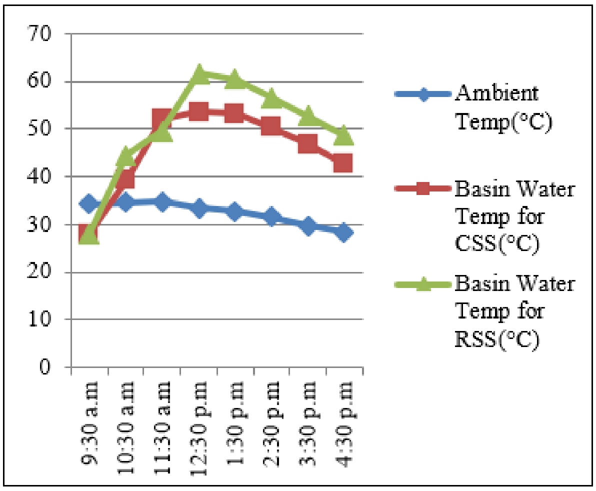


Figure 17: Hourly variation of basin water temperature with ambient temperature (11 - 03 - 2024)

A narrower temperature difference between the water and the glass cover enhances the productivity of the solar still. In Figure 18, the hourly fluctuations of the inner glass cover temperature are depicted for both the conventional solar still and the Revised Solar still. The maximum inner glass cover temperature recorded at 12: 30 p. m. for the conventional solar still was 48.3°C, while for the Revised Solar still; it was 54.5°C at 1: 30 p. m.

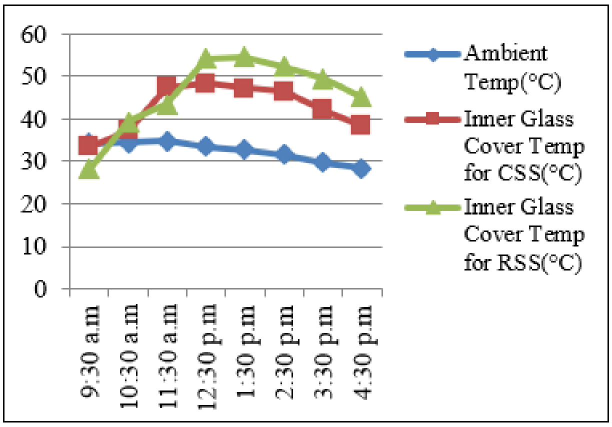


Figure 18: Hourly variation of Inner Glass Cover temperature with ambient temperature (11 - 03 - 2024)

From figure 19, the highest hourly distillate obtained at 12: 30 p. m. for the conventional solar still was 0.13 liters, while for the revised solar still, it was 0.17 liters at 1: 30 p. m. and 2: 30 p. m. respectively. The presence of gravel immersed in aluminium oxide nano - fluid, covered with black wick, enlarges the wetted surface area, allowing for greater absorption of solar radiation and elevating the temperature within the basin, thus facilitating faster water evaporation and resulting in a higher distillate output. The horizontal aluminium tube air - cooled condenser plays a crucial role in maintaining the temperature difference between the basin water and the glass cover. Vapour generated through water evaporation within the still is condensed within the condenser area, contributing to the overall distillate output.

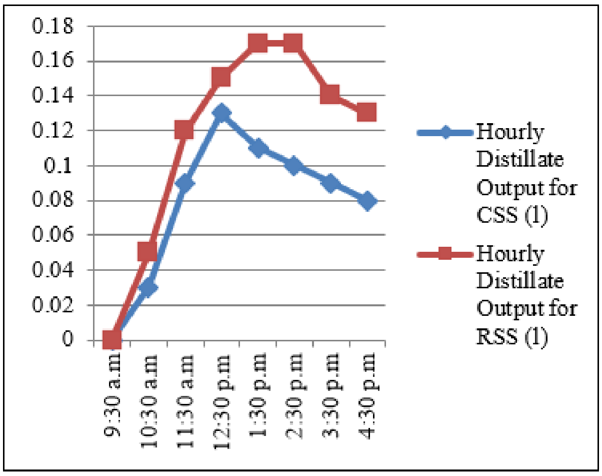


Figure 19: Hourly variation of distillate output with time (11 - 03 - 2024)

In Figure 20, graph illustrates a continuous increase in distillate production over time. The total distillate output obtained for the conventional and revised solar stills was 0.63 liters and 0.93 liters, respectively. The revised solar still yielded a total of 47.62% more distillate output than the conventional solar still.

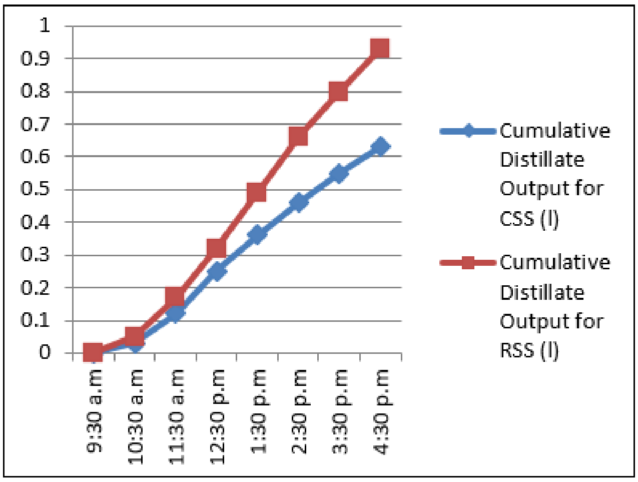


Figure 20: Hourly variation of cumulative distillate output with time (11 - 03 - 2024)

5. Conclusion

The primary drawback of traditional solar stills lies in their limited distillation output. To address this issue, a revised solar still was developed, incorporating different combinations of gravel, black cotton wick, and aluminium oxide nano - fluid (at a 1% weight concentration in saline water), along with the addition of a horizontal tubular aluminium air - cooled condenser. The main findings of the study are summarized as follows: The maximum basin water temperatures achieved for the revised solar still in Case - 1, Case - 2, and Case - 3 were 62.3°C, 57.9°C, and 61.7°C, respectively, though these values are contingent upon the maximum ambient temperature on a given day. The maximum hourly distillate outputs for the revised solar still in Case - 1, Case - 2, and Case - 3 were 0.18 liters, 0.17 liters, and 0.17 liters, respectively. The maximum cumulative distillate outputs for the revised solar still in Case - 1, Case - 2, and Case - 3 were 0.87 liters, 0.88 liters, and 0.93 liters, respectively. In each case, the revised solar still exhibited a total of 42.63%, 46.67%, and 47.62% higher distillate output than the conventional solar still. The attachment of a horizontal tubular air - cooled aluminium condenser in the revised solar still effectively maintained lower inner glass cover temperatures, contributing to the enhancement of distillate output.

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