Analytical study of a single slope solar still: experimental evaluation

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ABSTRACT

Even though water covers the surface of the Earth in three quarters, many nations face shortages of drinkable water due to rapid global population and industrial growth. Solar power emerges as an efficient solution, particularly in hot climates with water and energy scarcity. This research focuses on a practical solar solution known as a solar still, a basic apparatus designed to convert available salty water into potable water. In this study, a single-slope solar still using acrylic material is experimentally analysed, predicting daily distillate production under varying climatic conditions. Using heat and solar radiation, solar distillation offers a simple, affordable, and small-scale approach to clean water production. The solar still, utilizing acrylic sheets as a basin material, minimizes heat losses and enhances water evaporation rates, making it a promising technology for addressing water scarcity issues. The experimental analysis results revealed a distillate output of 420 ml per 0.49 m² per day.

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1. INTRODUCTION

Water is essential for the survival of all living organisms on our planet, encompassing humans, plants, and animals. It is widely distributed, constituting three-quarters of Earth's surface. The predominant portion, around 98%, is saline water found in oceans. By contrast, the other two percent provides fresh water for lakes, rivers, ice, and groundwater, meeting the many requirements of both people and animals. Nonetheless, only a restricted portion of this freshwater is readily available to humans. The natural processes, specifically the hydrological cycle, are crucial in supplying fresh water. Manokar [1] thoroughly investigated the factors influencing evaporation and condensation rates in passive solar systems. He suggested using low-thermal conductivity materials for basins and incorporating thermal storage materials to improve efficiency. These substances work to stop the atmosphere from losing too much heat. In the solar still system, the basin liner and salt water absorb sun radiation that passes through a transparent cover. The basin liner, which is distinguished by a comparatively high solar radiation absorptance, plays a crucial role as an absorber, as emphasized by Cooper and Read [2]. In practical applications, Duffie commonly utilizes plastic or metal sheets for basin liners [3]. Vijayasarthy *et al.* [4] proposed a solar distillation design incorporating a basin. It was creatively changed by replacing it with a small tank that had a lid and a way to release the steam that had evaporated. Different plastics and metal sheets, such as copper, aluminium, and steel [5], [6], each with its own cost and thermal conductivity characteristics. High heat conductivities are exhibited by copper and aluminium (k = 200 Wm-1K-1 for aluminium and 390 Wm-1K-1 for copper),but they are more expensive compared to galvanized steel, which has a lower thermal conductivity (k = 48 Wm-1K-1).

Experimental studies by Korada *et. al.* [7] determined an optimum fin spacing of 10cm for radiative heat transfer, a parameter crucial for solar engineering. The paper looks at ways to improve the efficiency of a desalination unit and a simple design for one that is connected to a photovoltaic thermal system. Furthermore, Tanaka [8] investigated how various inclination angles affected a basin-type solar still's performance and discovered that the ideal angle for the glass cover was roughly 30 degrees. Because acrylic has low heat conductivity, it was selected as the raw material for the solar still in this experiment. Aluminium fins were incorporated as a storage material to enhance condensation. Experimental studies by Vivek *et al.* [9] involves the construction of a solar still in a pyramid configuration, incorporating heat pipes within evacuated tubes. Aswathi and Rajesh [10] use compound parabolic concentrators (CPC) to increase the solar energy collection area, and coating the inside surface of the basin increases the absorption of solar radiation, with the addition of black stones inside the basin. Parvathy *et al.* [11] introduced a simplified and convenient method for regulating the integration of solar power into the grid, incorporating MPPT algorithm.

The primary goals of this work are to build an experimental setup for a single-slope solar still, use solar radiation to turn salty water into distilled water, monitor temperature variations in various components using thermocouples and a digital temperature indicator, and assess the solar still's efficiency, calculating the total water distillation per day, and evaluating the quality of the distilled water.

2. CONVENTIONAL METHOD

The traditional approach to assessing a single slope solar still is setting up a controlled experiment to gauge its output and efficiency [12]. A transparent glass or plastic sheet tilted at the ideal angle for condensation covers the heat-absorbing material basin, which is usually painted black to optimise solar energy absorption [13]-[19]. This is the still's configuration. The system is designed with insulation to reduce heat loss and carefully positioned temperature sensors to record the temperature of the water at different depths, the temperature of the glass cover, and the surrounding air. The intensity of the incident sun radiation on the still is measured using a pyranometer. Temperature and sun radiation data are collected at regular intervals throughout the day, and the amount of distilled water is monitored on a periodic basis using a collecting jar [20]-[25]. To learn more about the performance dynamics of the still, experiments are carried out in a variety of environments and water depths.

In comparison to more sophisticated suggested methods, the conventional approach has several drawbacks even though it offers a fundamental framework for assessing single slope solar stills [22]. The traditional method frequently lacks in-depth examination of heat transfer mechanisms and the impact of changing environmental conditions at a more granular level, instead concentrating mostly on simple measurements and efficiency computations [23]-[25]. Usually, it does not include cutting-edge materials or creative design changes that could improve performance [25]. Furthermore, combining solar stills with other renewable energy sources or hybrid designs that can function in low sun radiation environments may not be as feasible using the traditional approach. These sophisticated analyses and integrations are frequently included in proposed methodologies, providing a more thorough understanding and optimisation of solar still performance, increasing production and efficiency under a range of environmental circumstances.

3. PROPOSED METHODOLOGY

A single-basin solar still consists of a basin with a fin-equipped black-painted aluminium plate. A translucent glass cover ensures a hermetic seal around the solar still. Solar intensity, wind speed, ambient temperature, water-to-glass temperature differential, water's free surface area, absorber plate area, and inlet water temperature are some of the variables that affect how effective a solar still is. This simple water distillation process captures solar heat. The container is filled with contaminated water, and sunlight causes the water to evaporate, helped along by clear plastic or glass. The clean water vapour that results condenses on the upper surface and falls to the side, where it is gathered and removed. Figures 1 and 2 illustrates a schematic diagram and block diagram of a basic solar still, showcasing an insulated, black-painted aluminum pan containing shallow, impure water. A sloping glass cover, supported by a suitable frame, securely seals the pan to minimize vapour leakage.

3.1. Modeling of solar still

A CATIA model was created for the efficient basin area, measuring 0.65 meters by 0.75 meters, with a thickness of 4 mm. The lower vertical side of the still was set at a height of 0.30 meters, while the higher vertical side was elevated to 0.71 meters. The condensing cover was positioned at a 30-degree angle, and its thickness was maintained at 4 mm. Figure 3 depicts the imported CATIA model within the ANSYS workbench. Solar still losses can be categorized into three main types. Firstly, water leakage occurs over time due to the junctions of walls and the edges of the bottom surface, sometimes leading to significant leaks. This issue can be addressed by applying leak-proof materials to vulnerable areas. Secondly, vapour losses represent a major challenge observed consistently throughout the experimentation process. The primary cause of this loss is the presence of inlet and outlet holes, providing avenues for vapour to escape. Lastly, insufficient vaporization is noted during the morning and evening, where there is an inadequate accumulation of water drops to flow over the glass. This results in wastage of insufficient water drops.

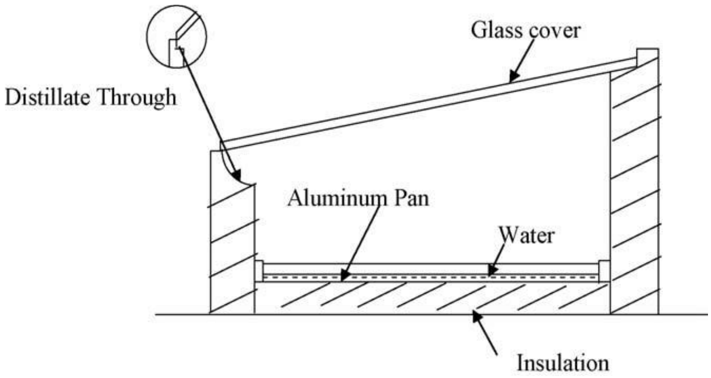

Figure 1. Solar still schematic diagram

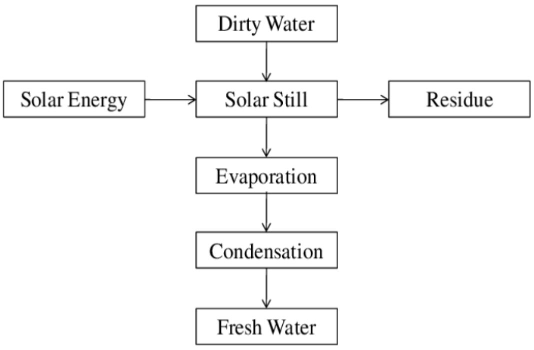

Figure 2. Block diagram of Solar still

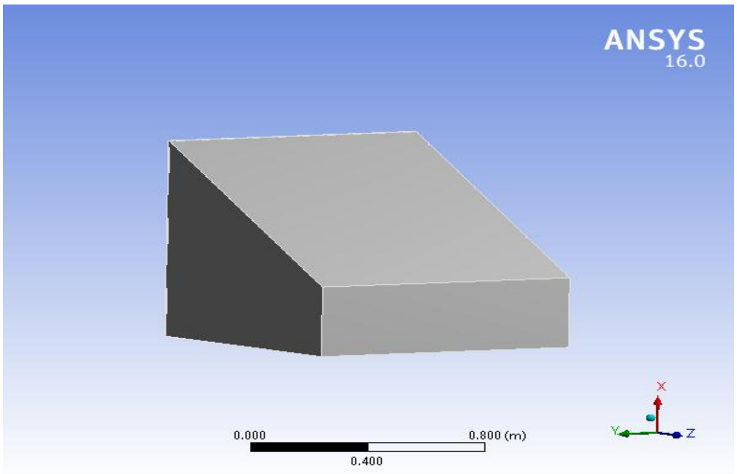

Figure 3. CATIA model of solar still

3.2. Material selection

Table 1 shows the material selection comparison of different materials.

Table 1. Material selection comparison

Part name	Material	Size	Purpose of selection
Still Basin	Aluminium Sheet with acrylic insulation	65*75 cm with 2mm thickness	Low thermal conductivity of acrylic and corrosion-resistant aluminium
Casing	Acrylic	4mm thick	Low thermal conductivity
Top Cover	Glass	71*77cm with 3mm thickness	High transmittivity
Heat Storage Material	Aluminium Fins	Diameter 18mm and height 12cm	High thermal conductivity and Corrosion resistance
Water Collector	Acrylic	(L shaped) 4mm thick	Low thermal conductivity

3.3. Data analysis

To assess performance, data analysis for a single slope solar still entails looking at temperature profiles, solar radiation, and distilled water yield. Regular temperature measurements are made of the water, the air within the still, the glass cover, and the surrounding area. The system's heating and cooling cycles are made visible by plotting these measurements to determine peak temperatures and when they occur. The efficiency of the solar still is calculated by dividing the total solar energy incident on the still by the energy needed for distillation. This requires determining the latent heat of vaporisation and the mass of distilled water. Due tothe bigger thermal mass requiring more energy to heat, efficiency trends show a drop with increased water depth and an increase on sunny days with strong solar radiation. The impact of solar radiation intensity on water yield is also examined in this investigation. A direct association is established between the volume of distilled water collected and solar radiation measurements, indicating larger yields on days with prolonged sunshine. A comparison of several water depths reveals the ideal depth for optimum effectiveness and output. The efficacy of single slope solar stills in harnessing solar energy for sustainable water purification is demonstrated by this thorough investigation, which offers insights into optimising the design and operating parameters of these units.

3.4. Experimental procedure

A predetermined amount of saline or dirty water is poured into the basin. The water's temperature, the air around it, and the amount of solar radiation are all measured initially. Sun radiation intensity and temperature (ambient, glass cover, and water) are measured throughout the day at regular intervals. Periodically, the volume of collected distilled water is measured. In order to account for variations in sun intensity, the experiment is carried out in a variety of settings, including different water depths, days, and environmental factors.

3.5. Fabrication process

Aluminium sheets are employed at the base of the basin, and a set of 25 aluminium rods function as fins. Each fin has a diameter of 18 mm and a height of 12 cm. The bottom of the bowl is painted black to improve absorption. Figure 4 visually depicts the aluminium fins serving as heat storage material in the setup. The water collector in the model is constructed using acrylic sheets. These sheets are cut into two long bars, which are then affixed to the lower vertical side of the solar still, forming an L shape. Acrylic cement solvent is used in the attachment process to secure the bars for effective water collection. Additionally, acrylic boxes are crafted from acrylic sheets, varying in sizes, and assembled using acrylic cement solvent to create functional boxes. Figure 5 illustrates this setup, showcasing drilled holes for specific purposes. A 20 mm diameter hole serves as the water inlet, a 16 mm diameter hole facilitates the passage of the thermocouple, and a 10 mm diameter hole is designated for the outlet of distilled water.

In this experimental setup, three K-type thermocouples were employed. Type K thermocouples are widely recognized for their prevalence and versatility in temperature monitoring applications. They are valued for their cost-effectiveness, high accuracy, and reliability across diverse temperatures. With a broad temperature range, Type K thermocouples prove suitable for various industrial and scientific processes. These thermocouples were strategically inserted into the solar still by creating holes on the rear side, as illustrated in Figure 6. A temperature indicator was utilized to measure the temperature, which takes input from the K-type thermocouples and provides temperature readings with an accuracy of 0.01 degrees Celsius. The power supply for the system was derived from a 9-volt DC battery. The initial experiment, conducted on

February 19, 2019, yielded the following results: water input: 8 liters; distilled water: 200 ml; maximum water temperature: 64 °C.

A significant observation during the experiment was the noticeable accumulation of water on the side and rear walls, suggesting the potential for collection. This accumulation held the promise of enhancing the efficiency of the solar still. Figure 7 visually captures water droplets accumulating on the glass cover, emphasizing the potential for increased efficiency.

Figure 4. Aluminium fins as heat storage material

Figure 5. Acrylic box and L shaped water collector with glass cover

Figure 6. Thermocouple's in solar still

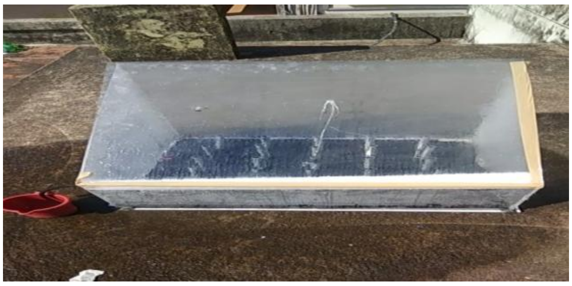

Figure 7. Water droplets accumulating on the glass cover

Following the modification to the setup, four additional inclined water collectors were incorporated into all the walls, and insulation using m-seal was applied to all edges. This resulted in an increase in both the distilled water yield and the maximum temperature. The second experiment, conducted on February 22, yielded the following results: (i) water input: 8 liters; (ii) distilled water: 420 ml; (iii) maximum water temperature: 69 °C; (iv) total losses: 720 ml; (v) remaining water: 6.8 liters. A notable observation during the experiment was the accumulation of sufficient water on the side and rear walls, which was effectively collected. Additionally, there was an observable rise in the maximum water temperature. Multiple experiments were conducted with both 8 liters and 2 liters of saline water from 9 am to 6 pm, wherein the distilled water was collected and measured. The water, glass cover, and fin temperatures were all measured. Specifically, for the 8L water input where the aluminum fin height was 12 cm, Table 2 provides the collected data.

Table 2. Data collected for 8L water input

Time duration	Aluminium fin temp. (in degree C)	Water temp. (in degree c)	Distilled water (in ml)	Glass cover Temp. (in degree C)
9am to 10am	33	29	-	30
10am to 11am	52	41	10	38
11am to 12pm	63	53	40	45
12pm to 1pm	71	60	55	51
1pm to 2pm	76	67	75	55
2pm to 3pm	75	69	80	53
3pm to 4pm	67	59	70	49
4pm to 5pm	58	49	55	40
5pm to 6pm	43	39	35	38

4. RESULTS AND DISCUSSIONS

4.1. Change in the temperature of the aluminium fin with time

Figures 8 and 9 depict the fluctuations in aluminium fin temperature over time. The aluminium fin serves as a reservoir for heat energy, dissipating it when the sun's radiation is at its lowest. The temperature of the water's upper surface can then be raised by this stored heat, which can speed up the evaporation process.

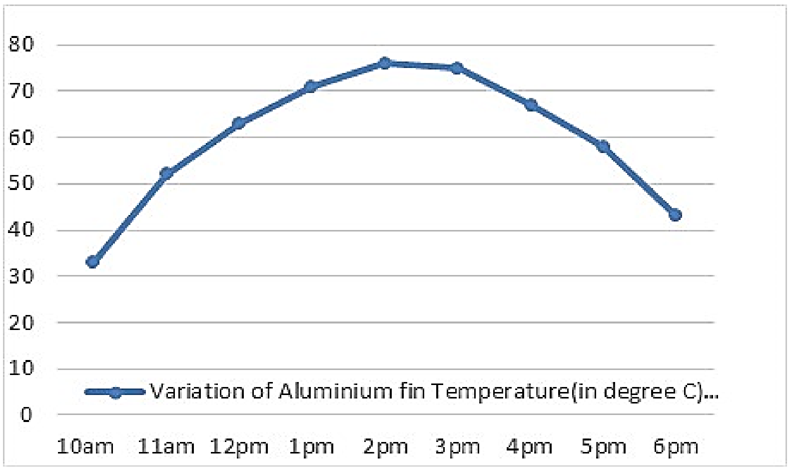

Figure 8. Change in the temperature of the aluminium fin with time

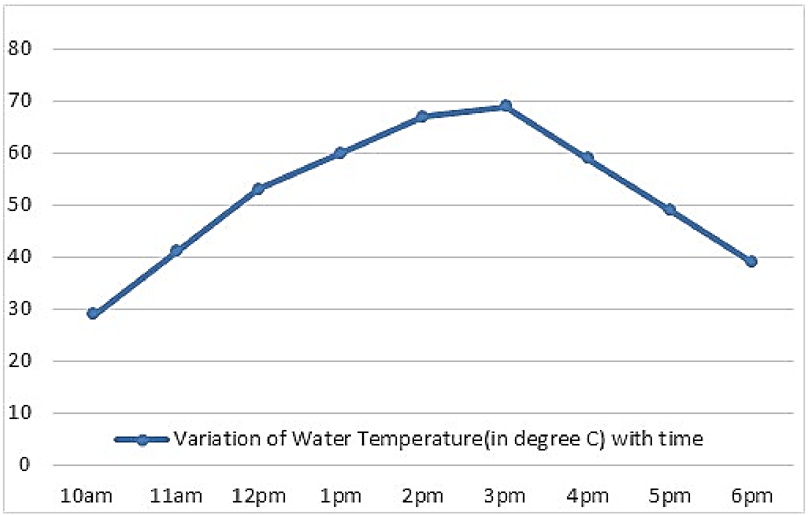

Figure 9. Changes in water temperature over time

4.3. Changes in glass cover temperature over time

The temporal variation in the temperature of the glass cover is shown in Figure 10. After evaporation, condensation occurs in a solar still, and the inner glass cover helps with this condensation. The temperature differential between the water and the glass cover has a significant impact on how well the solar still works. The experiment unequivocally shows that a larger distillate yield is directly correlated with a greater temperature differential between the water and the glass covers. On to Figure 11, where the temperatures of glass, water, and aluminium fins are highlighted in a comparative comparison.

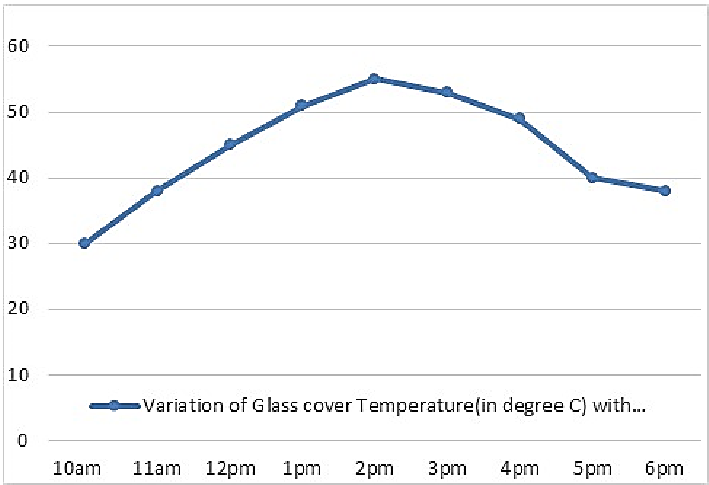

Figure 10. Changes in glass cover temperature over time

4.4. Comparison among temperature of Al fin, water and Glass temperature

Figure 11 shows, that the Comparison among temperature of Al fin, water and glass temperature.

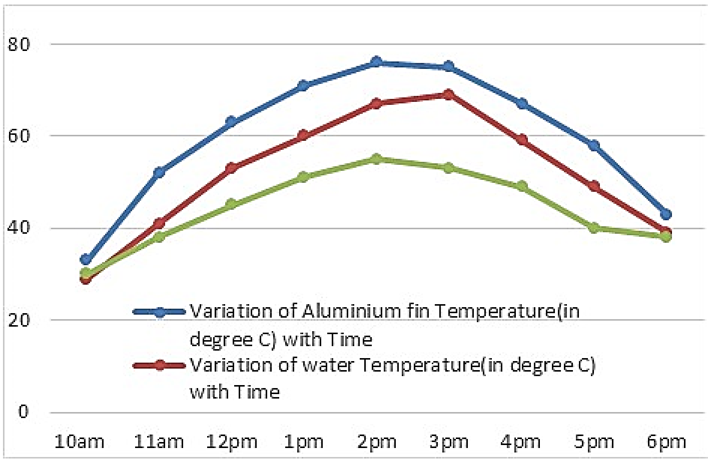

Figure 11. Comparison among temperature of Al fin, water and glass temperature

4.5. Changes in distilled water over time

The fluctuation in productivity over time is shown in Figure 12. The graph clearly shows that there is a notable yield of distilled water that occurs mostly between 2:00 PM and 4:00 PM. At this time, the glass is exposed to a significant amount of solar light, which raises the aluminium fins' temperature. In turn, this causes the brackish or saline water's heat conduction to increase. Notably, from 2:00 PM to 3:00 PM, the largest volume of distilled water—80 ml—is acquired. The findings highlight how sun intensity and the material used for heat absorption affect the amount of distilled water produced.

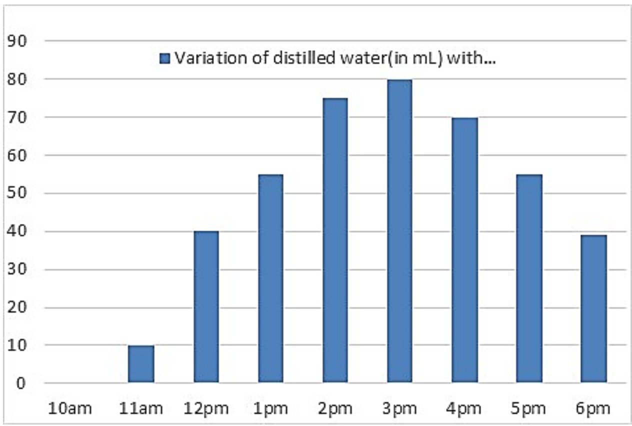

Figure 12. Changes in distilled water over time

Case (i): When the water input was 8 litres
Water distilled on the 1st day = 420 mL; Water distilled on the 2nd day = 270 mL; Water distilled on the 3rd day = 105 mL; Water distilled on the 4th day = 45 mL; Water distilled on the 5th day = 25 mL; Total distilled water = 865 mL. The efficiency of the solar still is 0.108125, or 10.818%.
Case (ii): When water input was 2L
Water distilled on the 1st day = 200 mL; water distilled on the 2nd day = 55 mL; water distilled on the 3rd day = 20 mL; Total volume of distilled water = 275 mL. The efficiency of the solar still is 0.1375, or 13.75%.
Quality of distilled water: After laboratory testing of distilled water, the following properties were obtained: PH of the distilled water = 6.8; conductivity of distilled water = 0.21 mS.

5. CONCLUSION

The main results of this investigation, which involves an experimental analysis of a single-slope solar still, are summed up as follows: i) The experimental analysis results revealed a distillate output of 420 ml per 0.49 m² per day. ii) In the solar still, the condensation process initiates after evaporation, and the inner glass cover facilitates it. The temperature differential between the water and the glass cover is still influenced by the sun's performance. The experiment demonstrated that a higher temperature difference increases distillate output. (iii) The solar system's efficiency is still contingent upon the water input. For an input of 8 liters of water, the observed efficiency was 10.8%. (iv) As a result of its low thermal conductivity, the acrylic sheet used as the casing increases the rate at which water evaporation occurs by reducing heat loss from the still to the bottom. (v) The maximum water temperature achieved was 69 degrees Celsius for 8 liters of saline water. (vi) Improved efficiency of the solar still was achieved by attaching additional guideways to collect water accumulating on the side walls. (vii) The conductivity of the distilled water obtained in this experiment was measured at 0.21µS/cm, significantly lower than that of seawater (56,000µS/cm) and closer to very pure water (0.05µS/cm). (viii) The pH of the distilled water obtained in this experiment was recorded at 6.8, falling within the normal range of 6.5 to 8.5 for pH in surface water systems, with pure water having a pH of 7.

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