Experimental investigation on the performance of a pyramid solar still for varying water depth, contaminated water temperature, and addition of circular fins

Mayilsamy Yuvarperiyasamy*a, Natarajan Senthilkumar*a, Balakrishnan Deepanra*b

*aSaveetha School of Engineering, Saveetha Institute of Medical and Technical Sciences, Chennai, Tamil Nadu, India - 602105
bDepartment of Mechanical Engineering, College of Engineering, Prince Mohammad Bin Fahd University, Al Khobar, 31952, Saudi Arabia

Abstract. The experimental investigation was meant to investigate the effect of water depth in the basin, the water temperature at the inlet of solar still, and adding circular fins to the pyramid solar still on freshwater output. The investigation was divided into three sections. The first area of research is to study effect of increasing water depth in the solar still, which ranged from 2 to 6 cm, second section concentrated on varying the inflow water temperature from 30 to 50°C, and third section investigated the influence of incorporating circular fins into the solar still basin on the water output and quality. The experimental findings showed that basin depth considerably impacts freshwater flow. The highest significant difference, 38%, was recorded by changing the water level in the basin from 2 to 6 cm. Freshwater yielded the most at a depth of 2 cm, totalling 1250.3 mL, followed by 1046 mL at a depth of 3 cm. A water depth of 4 cm produced 999 mL, whereas a water depth of 5 cm made 911 mL. The lowest production occurred at a water depth of 6 cm, producing 732 mL; furthermore, including fins at the bottom increased productivity by 8.2%. Elevating the temperature from 30 to 50°C of the inlet water led to a water output increase of 15.3% to 22.2%. These findings underscore the profound potential of harnessing solar energy to address global water challenges and pave the way for further advancements in efficient freshwater production.

Keywords: Solar still, Desalination, Water purification, Solar energy, Circular fins, Pyramid solar still

1. Introduction

Clean, and safe drinking water must be readily available for any population to survive. Freshwater makes up around 2.5% of the water on earth, whereas salt water makes up the rest, about 97.5%. Approximately 80% of the freshwater on earth is held in soil moisture and ice caps. The amount of freshwater on Earth that can support life is about 0.5% (El-Dessouky & Ettouney, 2002). The unequal distribution of freshwater globally has left communities most in need with insufficient access to this vital resource. As such, the freshwater shortage has become a worldwide problem in the current context. Therefore, creating techniques to turn saltwater into potable water is essential, especially in remote and dry regions. Solar desalination is a promising technology that can use copious solar energy. This method relies heavily on the solar still, an ingenious apparatus that speeds desalination. Furthermore, solar thermal energy may heat water efficiently, improving the efficiency of power plants (Ahmadi et al., 2017). Additional enhancements such as wicks, sponges, and fins were incorporated into a conventional solar basin to enhance its performance. The adjustments improved yield by 9.6, 15.3, and 45.5% (Velmurugan et al., 2008). Unlike regular, pyramid solar stills with curved wick surfaces showed better production and 33.3% more efficiency (Kabeel, 2009). A study by Tanaka and Nakataka (2009) found that incorporating a vertical plate absorber into spinning solar still results in a 57% increase in energy production compared to conventional solar stills. Wick material was tested by Murugavel and Srithar (2011) on absorber plates for solar stills that had differently oriented rectangular fins. Black cotton fabric is the best wick, according to research. Adding a water heater to the absorber shield and cooling the glass with an external fan increased solar still efficiency. The new method was 370% more prolific than other solar stills (Al-Garni, 2012). Different packing materials, like sand, coal, coconut coir, and wooden chips, were used in experiments with stepped solar stills. These tests were done using both experimental and numerical methods. The research showed that solar stills with 2 cm of water depth and coconut coir stuffing produced more yield than other setups (Alaudeen et al., 2014). Also, Gnandason et al. (2015) showed that adding rocks, fins, vacuum pumps, and other changes to solar stills made them more productive and found that solar stills with vacuum fans were more effective than other solar stills. To enhance the output of solar still, Sathymurthy et al. (2015) examined the application of a shield and a semicircular trough absorber. Using a barrier resulted in a 16.6% increase in output from the semicircular trough absorber over conventional stills. In the absorber plate of the solar still, Hansen et al. (2015) looked at various wick materials and wire silhouettes. They discovered that stepped wire mesh absorbers were 48.9% more productive than flat absorbers and 72% more effective than flat...
and stepped absorbers. They used a two-layer reflector and wick in a bent absorber solar still. The solar still with the bent absorber made 145.5% more than regular stills that used wick material (Omanakath, 2016). Also, the study by Panchal and Sathyamurthy (2020) had shown that certain wick materials and a pin-finned absorber base can improve solar stills. This study examines a single-basin solar efficacy by comparing its productivity with and without incorporating a porous fin. The study found that adding a porous fin to the pin-finned wick solar system resulted in a 24% increase in output. In addition, adding a porous fin led to a 42.3% rise in solar energy production compared to the standard design. In an earlier work by Haddad et al. (2017), a vertically moving wick was used to improve traditional solar stills. The goal of this change was to speed up the cooling process and, as a result, make it still produce more distillate water. The research says that a solar still with a wick that rotates vertically is 46% more proficient than a regular solar still. Nagarajan et al. (2017) used theory and experimentation to add barriers to traditional solar stills. The study indicated that solar stills with baffles produced 1.68 times more modified solar still (MSS). A separate experiment examined V-type solar still performance with various fibers. A half-covered wick resulted in an 8.2% increase in production (Sumenesh et al., 2017). Several wick materials were tested by Munisamy et al. (2017) to increase solar still output; fur material produced 40.8% more productivity than rayon, terry, and jute by 40.8%. Polyester production increased by 26.37%, while terry and jute cloth increased by 6.2%. Pal et al. (2018) examined the advantages of double-slope solar in terms of both the environment and economy, emphasizing the design of its specially tailored multi-wick basin. This study examines solar energy's economic and environmental implications, providing important details about its efficiency and longevity. Modi and Modi (2019) suggested that using a jute pile, black cotton fabric, two bowls, and a single slope would still be more effective. It was found that using a jute cloth pile instead of a black cotton fabric pile led to a 15.2% higher distilled yield. Omara et al. (2015) investigated the utilization of nanofluid, curved wicks, internal mirrors, and external condensers in solar still systems. The study demonstrated that using curved stems and aluminium oxide nanoparticles in solar stills resulted in a substantial output enhancement. Specifically, the improvement was 255% compared to traditional stills. Evaluated was a solar system with a single basin and a double-slope, single-basin solar system with distinct fins. The square concave fin produced 43.86% less energy than the circular open-fin solar still. The highest yield was recorded at a water depth of 10 mm (Jani & Modi, 2019). The research focused on an internally and externally enhanced two-sloped solar distillation system. According to test results, the upgraded solar produced an incredible 171.43% more energy than the standard solar (Gnanaraj & Velmurugan, 2019). It was determined how well a MSS used cotton sacks filled with sand and a circular solar still (CSS) worked at optimum water depth. The findings showed that CSS outperformed CSS (Dumka et al., 2019). A solar still with a single basin and a double slope was used in research by Murugavel et al. (2010) to store energy. Iron bits, pieces of cement concrete, washed stones, red brick, and quartzite rock were all put together. The study results show that using 3/4” quartzite rock significantly increased output compared to other materials used for energy storage. According to research by Ismail (2009), the daily usefulness of the solar system went down as the water level in the pond rose. This study was mainly about a horizontal solar still that worked in various salt conditions. It was found that the conical solar still produced 75.13% more each day than the standard solar still in a comparison study (Gad et al., 2015). According to comparative research, the triple basin square pyramid solar still design generates higher yields than the single and double basin versions (Hamdan et al., 1999). The pyramid-shaped system used by the normal solar system was nevertheless modeled after the Great Pyramid of Giza. The daily output averages for both types of solar stills were similar throughout the year (Fath et al., 2003). Kabeel and Abdelgaied (2020) looked at what would happen to the production rate of pyramid solar devices if copper absorber plates were switched out for graphite absorber plates. The researchers enhanced water vapor generation by reducing the upper glass cover temperature by applying a water layer. Effectiveness-wise, according to the study, the modified square pyramid solar still (MSS) was superior to the standard square pyramid solar still. The production of distilled water rose by 20% when paraffin wax was used as a phase change material (PCM) in a pyramid-shaped still (Sathyamurthy et al., 2014). Existing literature and prior research highlight that only a few experimentations have explored the impact of varying inlet-contaminated water temperature on the productivity of the pyramid solar still. Most literature focuses on enhancing the solar still design by incorporating fins and insulation materials. This research aims to optimize solar still performance through experimentation and design improvements. This investigation is divided into three parts. The water depth is varied from 2 to 6 cm in the first part to find the optimal depth. The second part of the investigation is the impact of different water inlet temperatures from 30 to 50°C on pyramid solar still yield. The third part concentrates on solar still productivity by adding circular fins at the absorber basin liner.

2. Experimental setup and procedure

This study emphasizes on comparing the production output and quality of potable water obtained from the conventional pyramid solar still and the modified pyramid solar still. The proposed model of pyramid solar still consists of circular fins attached in the absorber basin liner and an external heater for preheating the inlet water and difference in water depth.

2.1 Conventional pyramid solar still

Figure 1 illustrates the schematic view of the conventional solar still. This pyramid solar still has three layers of insulation made of glass covers sandwiched between an interior structure made of galvanized iron sheet and an exterior layer made of galvanized iron sheet (Diabii, 2022). The depth of the glass plate is 7 mm, the height is 30 cm, the width is 65 cm and the slope angle is 35°. The solar base still has an area of 0.38 m² and a 35 cm height, with a wall thickness of 1.3 mm, including the galvanized iron sheet. The outer surface area is 0.50 m², with a height of 35 cm, and is insulated by a polyethylene layer 6 cm thick.

2.2 Proposed Experimental Setup

2.2.1 Pyramid solar still with varying water depth

The productivity of the solar still is mostly affected by the water depth. Since solar still runs only on solar radiation and requires no additional energy source, its output highly depends on the water depth. The investigation focuses on the effects of different water depths (2–6 cm) on the productivity of solar stills. Based on the experimental findings, it is necessary to establish an optimal water depth for future investigations.

2.2.2 Pyramid solar still with varying water inlet temperature

Changing the water intake temperature may affect the solar desalination system's overall performance and efficiency. Productivity may rise due to warmer water at the intake, as it takes less energy to attain the appropriate evaporation
temperature (Le et al. 2021). To raise the productivity of the pyramid solar still, the water intake temperature is adjusted between 30 and 50°C. The external heater heats the inlet water before entering the solar desalination system as shown in Figure 2.

2.2.3 Pyramid solar still with circular fins

Fins are add-ons that may be used to enhance the solar still’s surface area. As the water’s surface expands, more heat can be transferred to it, causing it to gradually heat up (Aktaş et al. 2019). A mild steel circular pipe with 0.04 m diameter and 0.08 m height is incorporated in the absorber basin. Six fins were considered for this experiment. The percentage of space occupied in the pyramid solar still absorber basin was used to calculate the number of fins in the absorber basin. These fins are an essential part of the design to shorten the preheating period before the salty water from the basin evaporates (Yuvaperiyasamy et al. 2023). Figure 2 shows the proposed solar still having circular fins and an external heater.

2.3 Experimental Procedure

Before starting the desalination of sea water process at the base, sanitation is an essential step. The water in the ground evaporates as the temperature increases and then condenses on the glass cover. The glass lid contains a container at its base holding condensed water. A digital thermal instrument with an accuracy of +/− 1 degree Celsius is used to monitor the temperatures of the glass and water throughout the experiment to retain reliable data. In addition, a solarimeter that measures solar radiation intensity with an accuracy of +/− 1 W/m² is used. A digital vane anemometer with an accuracy of +/− 0.1 m/s measures wind velocity. The distillate production is determined with a 2-liter container and a 5-milliliter measurement precision (Gad et al., 2015). The experiment was conducted in Pongalur, Tamil Nadu, India (10.9729°N, 77.3698°E) from May 15 to 19, 2023. Wind velocity, solar radiation, and basin plate temperature are measured hourly, along with the water temperature to be treated, distilled water, and glass cover.
Hourly outputs are determined for both the conventional solar still and the newly constructed pyramid solar still.

3. Result and Discussion

3.1 Solar radiation, water and ambient temperature variations

The experiment is conducted over five days, from May 15 to May 19, 2023, and the hourly variations in solar radiation during these days are measured. The graph demonstrates the hourly fluctuations in solar radiation over these five days.

A consistent pattern in solar radiation is observed across all five days. The highest solar radiation values are recorded around midday, between 13:00 and 14:00 hrs, with readings of 963, 980, 983, 992, and 979 W/m² for each respective day. Based on the solar radiation readings obtained over these five days, we can confirm the consistent efficiency of the system throughout this period. As depicted in Figure 3, solar radiation peaks around midday, between 13:00 and 14:00 hrs, gradually diminishing to its minimum value by 18:00 hrs. The sun is directly above the earth at noon, and solar radiation peaks at that time, which causes sunlight to go through the atmosphere at a shorter route and a perpendicular angle to the earth's surface, reducing absorption and scattering. Because of the sun's lowered angle in the evening, there is less solar radiation intensity because of a shallower angle of incidence and a longer atmospheric path (Sathyamurthy et al., 2015).

Figure 4 displays the experimental results indicating the hourly ambient temperature variations over the five days. The highest temperatures are recorded between 15:00 and 16:00 hrs, with a gradual decrease in temperature during the late afternoon hours. Higher temperatures intensify evaporation by imparting additional thermal energy to water, accelerating the transition of liquid to vapor. This increase in vapour production increases the overall production of freshwater. In contrast, lower temperatures cause the vapour to give up its thermal energy and return to liquid form during condensation (Yarramsetty et al. 2023). Condensation is facilitated by cooler conditions, maximizing freshwater yield. In a solar still system, optimal temperature regulation is required to balance evaporation and condensation to produce more purified water.

Figure 5 depicts the variation in water temperature across different depths (ranging from 2 cm to 6 cm) within the basin. The water temperature reaches its maximum of 75.4ºC at around 13:00 hrs for a water depth of 2 cm. It then gradually decreases to 43.7ºC by 18:00 hrs. The water temperature at a depth of 3 cm reaches 69.3ºC around 14:00 hrs. Then it drops to 39.2ºC by 18:00 hrs. This observation reveals that elevating the depth from 2 cm to 3 cm results in an 8% reduction in maximum temperature during the morning, with a subsequent 1% reduction by the evening. This aspect can be qualified for the thermal storage capacity of the water basin. At 14:00 hrs, the water temperature measures approximately 58ºC for the 6 cm depth, decreasing to around 38ºC at 18:00 hrs. Because of the reduced thermal mass, a shallower depth causes heating to occur more quickly, raising the temperature during the sun's strongest hours (Larik et al. 2019). Conversely, a deeper depth has a larger thermal mass, resulting in lower daytime temperatures and slower heating. The pattern of hourly fluctuations is as follows: during the day, temperature changes occur more quickly at shallower depths. This variation is attributed to the greater thermal inertia of the water basin, as previously reported in existing research (Omara et al., 2016).
3.2 Effect of solar still performance due to change in water depth

The hourly output fluctuation of a pyramid-shaped solar still at different depths, from 2 to 6 cm, with intervals of 1 cm, is shown in Figure 6. The variations in water output resulting from changes in depth in the solar still are recorded as follows: The weights per unit area for different depths are 1.24 kg (3.42 kg/m²) for 2 cm, 1.03 kg (2.89 kg/m²) for 3 cm, 1.02 kg (2.76 kg/m²) for 4 cm, 1.00 kg (2.6 kg/m²) for 5 cm, and 0.74 kg (2.02 kg/m²) for 6 cm. The findings show that around 13:00 hrs, at a depth of 2 cm, the highest freshwater output of 232 mL occurs. In contrast, the highest freshwater yield occurs at 15:00 hrs, with a volume of 232 mL at a water depth of 6 cm.

Figure 7 shows the total freshwater output of the recommended system at different water depths. At a water depth of 2 cm, the largest yield of 1250.3 mL is achieved, followed by 1046 mL at a depth of 3 cm. At 4 cm depth, the production equals 999 mL, and at 5 cm depth, the production is 911 mL. The lowest output occurs at a water depth of 6 cm, yielding 732 mL. The water heat volume increases with the inlet's temperature rate. Hence, the yield is improved with the increase in the temperature at the inlet. After 14:00 hrs, the water output reached the same efficiency regardless of the water inlet temperatures. The entering water's temperature significantly impacts the distilled water produced in solar still. Raising the temperature at which water is introduced increases evaporation by increasing the water's thermal energy. The increased energy promotes a faster conversion of liquid to vapour, leading to greater evaporation and freshwater production (AlRubaiea et al., 2021).

In contrast, lower water temperatures decrease the evaporation rate, necessitating additional time and energy to achieve the boiling point and initiate efficient evaporation. Consequently, there is a decline in the overall rate of freshwater production. Precise temperature regulation and control of the incoming water is paramount to optimize the efficacy and output of freshwater within a solar still system. The solar still operates more efficiently due to the elevated temperature of the contaminated water (He et al., 2023).

3.4 Effects of Circular fins

Fins on absorber plates are positioned at the foot of the basin to enhance solar radiation absorption in the solar still. The experiment shows that preheating the basin takes less time, which boosts output. Including fins at the bottom increases production by 8.2%, as seen in Figure 9. Fins improve heat...
dispersion and absorption significantly in a pyramid solar still. The fins, often made of very efficient heat conductors, increase the still's internal temperature and enhance solar radiation absorption. Elevated temperatures accelerate evaporation and condensation, resulting in an augmented yield of distilled water. Despite the lack of fins, the solar still efficiently absorbs heat from the base material, potentially slowing down the condensation and evaporation processes. Lower interior temperatures and a less efficient thermal distribution might reduce the overall effectiveness of water collecting (Hu et al., 2023).

3.5. Analysis of water quality

The water quality test was conducted at the Tamil Nadu Water Supply and Drainage Board (TWDB) in Chennai Malai, Tamil Nadu, India. Solar stills' assessment of water produced relies on evaluating its physical and chemical properties. The primary purpose of a solar still is to generate water that meets further drinking standards and is saline-free and to remove various suspended and dissolved particles that cause turbidity. The water in the basin begins to evaporate off the water's surface when it is heated by incoming sun radiation, precipitating all dissolved particles and suspended contaminants identical to boiling water. The distillate potable water obtained from optimal conditions quality is compared with the inlet saline water quality as presented in Table 1.

The desalination process lowered the pH of the sample water from 7.89 (alkaline) to 6.93 (nearly neutral) which makes it suitable for drinking as per the WHO standards. Typically, the total dissolved salts (TDS) in fresh water is below 1,000 ppm. TDS between 1,000 and 10,000 ppm defines brackish water. The TDS range for saltwater is between 10,000 and 35,000. In hypersaline water, the TDS level is more than 35,000. Before desalination of saline water, the TDS measured is 21,000 ppm whereas post-desalination it is drastically reduced to 48 ppm which is well below the WHO standards. Some aquatic organisms can't handle high chloride levels seen in waterways. The likelihood of corrosivity of the water and the overall quality of water for drinking are both worsened by the existence of chloride. Hence it is necessary to measure the chloride ions levels in water before and after desalination. The reduction in TDS and chloride ions by desalination is due to the effective evaporation of saline water with the proposed experimental setup that produces the quality distillate. As a result of the existence of salt ions, the electrical conductivity of saltwater is typically about 50,000 μS/cm, whereas that of freshwater ranges from 0 and 1,500 μS/cm. The electrical conductivity of the saline water is 29,000 μS/cm, and distilled water is 57 μS/cm. The desalination removes most of the salt ions present in the saline water and hence there is a decrease in electrical conductivity by 99.80%. One measure of water quality is its turbidity, or degree of clarity. Turbidity is often caused by the presence of suspended contaminants in water. The turbidity level of the sample and distilled water are 306 NTU and 0.5 NTU. It shows that 99.83% turbidity is removed from the sample seawater by the desalination process. Water characteristics are greatly improved with over 99% removal of contaminants and dissolved salt after desalination using the proposed pyramid solar still attached with circular fin and an external water heater.

4. Conclusion

The present investigation was carried out in five days of observation, during which hourly fluctuations in sun radiation were meticulously documented. The study demonstrated the intricate relationship between water depth and freshwater productivity. The optimal water depth for achieving the highest productivity was 2 cm, with greater depths resulting in diminishing yields. Water productivity is significantly reduced when the water height is enlarged from 2 cm to 6 cm. The most significant difference of 38% was recorded on altering the water depth from 2 cm to 6 cm. The maximum productivity achieved at the 2cm water depth is 1250.3 mL, whereas the maximum yield at the 6 cm is 732 mL. From this, the water depth has a more significant influence on freshwater production. This underscores the trade-off between depth and productivity, a crucial consideration when designing effective solar still systems. A significant advancement was the strategic integration of absorber plate fins at the base of the basin. The reduction in preheating time, coupled with an 8.2% improvement in productivity, validates the positive impact of these enhancements on system efficiency. This innovative design improvement has the potential to enhance solar still performance substantially. Also, increasing the water temperature at the inlet from 30 to 50 degrees Celsius enhances the water output from 15.3% to 22.2%.

Table 1

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<th>Properties</th>
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<th>Sample seawater</th>
<th>Distilled water</th>
<th>% Removal</th>
<th>Drinking water quality standards from WHO</th>
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<td>pH value</td>
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<td>6.93</td>
<td>99.83</td>
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<td>Turbidity</td>
<td>NTU</td>
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<td>0.51</td>
<td>99.83</td>
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<td>Total dissolved solids (TDS)</td>
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<td>14</td>
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These findings contribute to the broader discourse on sustainable freshwater generation using solar energy. The insights gleaned from this study can inform the refinement and implementation of solar still systems in water-stressed regions. As the world seeks novel solutions to pressing environmental challenges, this study's information and empirical evidence provide a pragmatic pathway for optimizing solar still efficiency and advancing our pursuit of a more water-secure future.

Future Work

The efficiency of the solar still may further be enhanced by incorporating different energy storage materials with high specific heat values and thermal conductivity, and environmental or sustainability aspects related to the pyramid solar still will be considered.

References


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