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Technical Note Article

Thermal Investigation of Single Slope Solar Still by Using Energy Storage Material

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ABSTRACT

In this research, a piece of copper scrap was placed in the 1m × 1m base of a single-slope solar still. An automated system steadily dripped salt water into the basin of the solar still. The experiment utilized dripping salt water and energy storage materials such as copper and brass scrap. Research has shown that the presence of copper scrap in the basin, combined with a shallow layer of salt water, has a significant impact on the distillate output. However, the high thermal capacity of the salt water in the basin can lead to reduced production. As more salt water is added to the basin, the temperature difference between the water inside and the glass cover increases. Based on the experimental results, the calculated yield is satisfactory, and the overall thermal efficiency remains at 71.3%. The production rate is also influenced by the diffusion process on the south-facing condensing cover. The temperatures of water, glass, and air, as well as their combined effects, are measured and analyzed.

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1. INTRODUCTION

Contamination of natural and artificial water supplies is a major contributor to the global fresh water crisis (Zhang et al., 2022). The use of solar distillation as a radical, forward-thinking approach is recommended as part of the overall solution. A basin can be built by using only readily available materials Still, many scientists have attempted and failed to find a way to boost distillation output. Researchers (Beemkumar et al., 2017) (Dhaidan & Khodadadi, 2017) (Lamnatou et al., 2019) (Liu et al., 2020) (Rasheed, 2020)found that decreasing the amount of water used in the still increased the yield. In addition to boosting distillate yield and solar energy absorption, adding dye to the basin water has other advantages (P. M. Cuce et al., 2021). There are a few strategies to improve the distillate production process, and one of them is the use of salt water and other absorbent materials. Researchers (Dhivagar et al., 2021) maximized the solar energy absorption of charcoal by using it in conjunction with other materials, while other authors (Xiao et al., 2019) relied on rubber mates to do the same. In an effort to increase output, scientists (E. Cuce et al., 2020) (Nagaraj et al., 2020;) (Panchal et al., 2017) performed experiments that involved adding "brass" components like glass, rubber, and brass gravel. It is crucial that water be distributed uniformly across the basin. Researchers in a recent study (Bhardwaj et al., 2020) soaked their printed materials in water before mailing them. The authors (Imran et al., 2020) proposed using a method to store daytime energy surplus for night time evaporation in a conventional still. This article identifies an evaporation zone and a heat storage zone within the basin water. About 35% of the solar heat is absorbed by water each day, according to their estimates. The researchers utilized a basin made of brass granite gravel, measuring 1 m long, 0.5 m wide, and 6 mm thick.

Storing the heat generated during the day in the blue metal scraps of solar stills, as described by author (Duan et al., 2020), allows the process to be repeated at night. Testing has shown that adding a layer of water in between red brick pieces, quartzite rock, cleaned scraps, cement concrete parts, and ferrous scraps significantly increases productivity. In recent studies, the authors (Bhardwaj et al., 2019) distilled liquid using a shallow basin of water and various wick materials.

The impact of combining beach sand with paraffin wax as a composite heat energy storage material is studied. Experiments are conducted in a solar still equipped with a composite heat storage material (SSCHSM), and the results are compared to those obtained in a solar still using a sensible heat storage material (SSSHSM), a solar still using a latent heat storage material (SLHSM), and a conventional solar still (CSS) (Sampathkumar et al., 2023)**.** The most practical solution to the global water issue is the use of desalination techniques driven by renewable energy sources since they do not deplete current energy sources, which causes ecological imbalance. Coupling solar stills with photovoltaic systems is becoming increasingly popular as a means of solar desalination (Suraparaju, Sampathkumar, et al., 2022)**.** Theoretically, the system was only around 31.58% efficient, although both the traditional and modified desalination systems achieved experimental

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efficiencies of about 36.28 and 78.86%, respectively. Changing the absorber material to copper, which is very thermally conductive, significantly increased system temperatures and, in turn, the system efficiency and yield (Suraparaju, Jha, et al., 2022).

By increasing the condensation rate using natural fibres on the glass cover, this study aims to assess the long-term viability of solar stills. Banana fibres (BF) and jute fibres (JF) are used to cover the solar still glass, both of which are readily available and eco-friendly (SS). The absorbency, retention, and porosity of natural fibres are crucial factors in increasing the condensation rate (Suraparaju & Natarajan, 2022c). Energy use to convert salt or brackish water into potable water might be one solution to this issue. In order to achieve long-term sustainability, the global community is moving away from traditional energy consumption patterns. When compared to other renewable energy sources, solar energy has higher efficiency and greater availability (Suraparaju et al., 2023). The solar still is one of several solar energy-driven desalination methods that may desalinate accessible saltwater or brackish water at low costs and with fewer infrastructure requirements. However, solar stills have a low freshwater yield, and many methods are being studied to prove their efficiency (Suraparaju & Natarajan, 2022b).

Incorporating a corncob filtration system improved scaling prevention over simply recirculating water through the hoses. In addition to producing more pure water per unit of energy expended, combined SPDC and LTTD systems are more cost-effective than solar stills (Suraparaju, Arjun Singh, et al., 2022). The results show that the RT-58 PCM can provide a higher yield than the traditional solar still (CSS) that did not use PCM. The efficiency of a solar still equipped with PCM is 46% higher than that with CSS. In addition, the cost per liter of freshwater produced and the payback period were shown to be lower for the solar still with PCM than they were for CSS (Sahu et al., 2022). The efficiency of SSGC is higher than that of CSS by roughly 19.1%. The Payback Time (PT) for obtaining one liter of clean water from SSGCF is 3.9 months, whereas the PTs for obtaining one liter of clean water from SSGC and CSS are 5.5 and 7.1 months, respectively (Suraparaju & Natarajan, 2022a).

This research presents the theoretical design and testing of a thermal storage component-based single-slope solar still. Copper and brass scrap is immersed in saline water one at a time to determine the technique efficacy.

2. DESIGN OF THE SYSTEM

The outer and inner plywood casings of the still are identically sized at 1 square meters. Air gaps in enclosures can be filled with glass wool, which has a heat conductivity rate of 0.0042 W/mK. Splitting the difference of 0.10 m between the front and back walls is done. Considering the latitude of the site, a glass dome with a condensing surface slope of 11° makes the most sense. According to Figure. 1, the experiment made use of a solar still setup in a single-slope configuration. Through a j-shaped tube linked to the front wall, distillate pours into a measuring jar (Manente et al., 2016) (Wu & Lin, 2015). It consists of galvanized iron sheets, coated brass for maximum solar absorption, and thin copper sheets bonded together (Qu et al., 2015). By controlling the rate at which seawater is passed into the basin, its floor has been brought to its lowest point. (Jamel et al., 2013) The gate valve in the saltwater tanks delivers water to the drip system, which consists of horizontal heat transmission pipes with drip buttons at a depth of 0.10 m within the basin (Baral et.,2015)

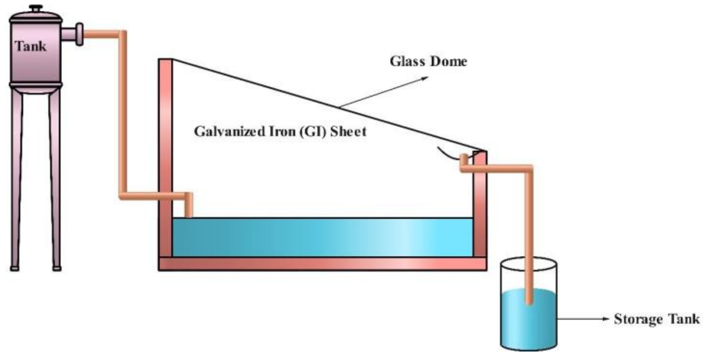


Figure 1. Schematic view of a solar still.

Copper-constantan thermocouples are used for accurate temperature readings in the basin, salt water, and condensation lid. Air temperature and solar radiation can be evaluated with the help of digital thermometers and radiation monitors, respectively. Table 1 summarizes key properties of common energy storage material.

Table 1. Properties of Energy-Storage Materials

Constituents	Density	Thermal conduction	Latent heat capacity
	g/cm³	(W/mK)	(kJ/kg)
Copper scrap	8.6	386.00	206
Brass scrap	3076	2.07 – 2.91	754

3. TEMPERATURE ANALYSIS

3.1. Transmission on Glass top

The condensing glass was covered with light from a wide range of directions and at variable intensity, all of which depended on the Earth's latitude (Jaafar & Hameed, 2021). If researchers want to determine the amount of energy absorbed by the water in the basin, they need to consider both the radiation energy received by the cover glass and the temporal variation in the transmittance of the cover glass. A theoretical evaluation is conducted, taking into account factors such as the radiant energy from the horizontal surface and the consistent transmission of the cover glass. The liquid within the still is heated by the solar energy that enters through the south-facing glass top (Sampathkumar & Natarajan, 2021).

$$Q_i = Q_s \tag{1}$$

where $Q_s = A_s I_S$.

Using this formula, which assumes all south-facing coverings are open at all times (Elsheikh et al., 2021) (Khairat Dawood et al., 2021)the authors can estimate the total solar radiation entering the still from the south:

$$Q\tau = Q\tau_S \tag{2}$$

where $Q\tau_S = \tau_S A_g I_S$

Based on the incidence angle (θ) of solar radiation, the percentage of diffused radiation (Kd), and the breadth of the glass cover (d), the authors (Labied et al., 2020) derived an equation to forecast the glass transmittance.

3.2. Energy balancing equation

When solar rays enter the basin through the glass top, they heat up the surface of the salt water, causing it to evaporate. Convection, radiation, and evaporation all play roles in transferring heat from the water surface to the base of the glass. Since the water and glass have different partial pressures, heat and mass are transferred from the water surface to the covering via evaporation. Some of the latent heat caused by the water vapor during evaporation is transmitted to the exterior of the container when the vapor condenses on the bottom of a glass container. Bottom and side walls are responsible for some of the heat loss to the environment through conduction and convection. With drip irrigation, salt water can gradually enter the basin and the basin's fresh and saltwater masses can achieve thermal equilibrium through sensible heat transfer.
The energy balance equations have been formulated under the following assumptions:
(i) Glass surface temperature is uniform across its entire area.
(ii) In order to prevent any vapor from escaping the still, the mechanism is hermetically sealed.
(iii) The small slope of the cover ensures that the glass top and the water surface are at right angles to one another.
Glass cover

$$I_g\alpha_g A_g + h_1 A_W(T_W - T_g) = h_2 A_g(T_g - T_a) \quad (3)$$

Basin water

$$(m_w C_w + m_{em}C_{cm})\frac{dT_w}{dt} = Q_\tau\alpha_{bw} - h_1 A_w(T_w - T_g) - h_3 A_{bs}(T_w - T_a) - h_{fw}(T_a - T_w) \quad (4)$$

The expression for T_g., obtained by solving Eq. (3), is as follows (Nazari et al., 2019a)

$$T_g = \frac{I_g\alpha_g A_g + h_1 A_w T_w + h_2 A_g T_a}{h_2 A_g + h_1 A_w} \quad (5)$$

wher

$h_1 = h_{cwg} + h_{rwg} + h_{ewg}$

$h_2 = h_{rga} + h_{cga}$

$h_3 = h_{ta} + h_{sa}$

$T_{sky} = (T_a - 6)$ is the apparent sky temperature

The following form (Nazari et al., 2019b) (Arunkumar et al., 2019) is obtained by making the necessary changes to Eq. (4):

$$\frac{dT_w}{dt} + PT_w = Q \quad (6)$$

where

$$P = \left(\frac{h_1^2 A_w^2}{(m_w C_w + m_{em}C_{cm})(h_2 A_g + h_1 A_w)}\right) - \left(\frac{h_1 A_w + h_3 A_{bs} - h_{fw}}{m_w C_w + m_{em}C_{cm}}\right)$$

$$Q = \frac{Q_\tau\alpha_{bw}}{m_w C_w + m_{em}C_{em}} + \frac{h_1 A_w I_g\alpha_g A_g + h_1 h_2 A_w A_g T_a}{(m_w C_w + m_{em}C_{em})(h_2 A_g + h_1 A_w)} + \frac{(h_3 A_{bs} - h_{fw})T_a}{m_w C_w + m_{em}C_{cmm}}$$

The generic form of the solution to Eq. (6) is as follows (Shoeibi et al., 2022):

$$y \cdot e^{\int p \cdot dt} = \int Q \cdot e^{\int pdt} \cdot dt + c \quad (7)$$

An expression for T_w is

$$T_w = \frac{Q}{p} + c \cdot e^{-pt} \quad (8)$$

Under the initial conditions, Eq. (8) holds when t=0, $T_w = T_{wi}$

$$c = T_{wi} - \frac{Q}{p} \quad (9)$$

By adjusting c in Eq. (8), it was obtained that

$$T_w = \frac{Q}{p}(1 - e^{-pt}) + T_{wi} \cdot e^{-pt} \quad (10)$$

The water temperatures in the basin and glass can be determined with great precision using Eqs. (5) and (10), respectively.

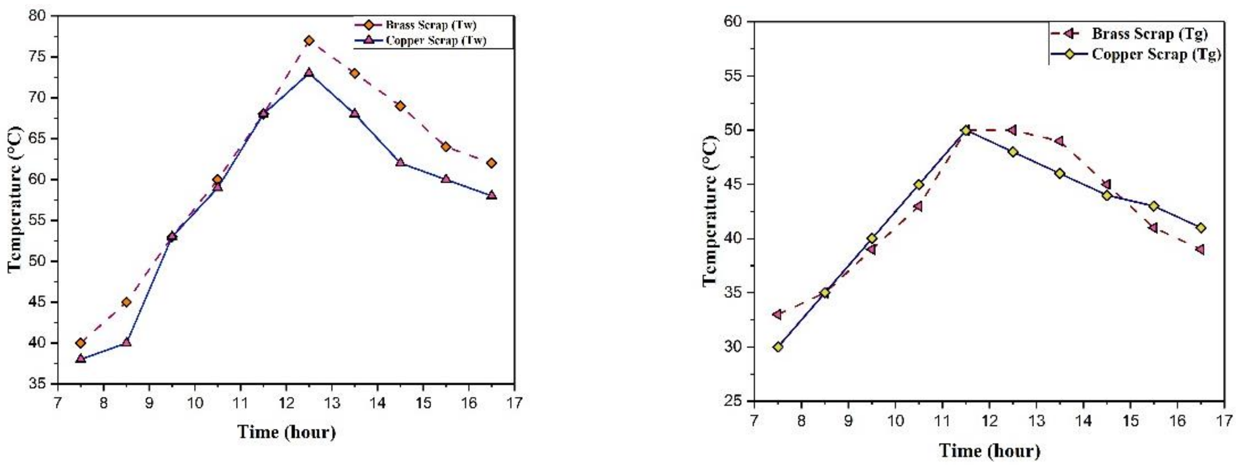
Distillation yield per still basin is calculated using

$$m_e = \left(\frac{h_{ewg}(T_w - T_g)}{L}\right) \times 3600 \quad (11)$$

The still efficiency is determined by (Abdelgaied et al., 2021)

$$\eta\% = \frac{M_e L}{A_b \int I_s \Delta t} \times 100 \quad (12)$$

where Δt is the duration of time in which solar radiation is quantified.



(a) (b)

Figure 2. Evaluation of Temperature for (a) water and (b) glass cover.

4. RESULTS AND DISCUSSION

The analytical response is derived by solving the energy balance equations to analyze the numerical findings obtained with the following design variables:

$A_g = 1.72\ \mathrm{m}^2;\ A_w = A_b = 1.6215\ \mathrm{m}^2;\ C_w = 4287\ \mathrm{J/kg°C^{-1}};$

$m_w = 14\ \mathrm{kg};\ m_{em} = 32\ \mathrm{kg};\ A_{bs} = 0.15\ \mathrm{m}^2;$

$\alpha_{bw} = 0.91; \alpha_g = 0.06;$ L = 2386000 j/kg

$V = 1.8\ \mathrm{m/s}, K = 0.042\ \mathrm{W/mk}.$

$\sigma = 6.19 \times 10^{-8}\ \mathrm{W/m^2k^4}$

The sun radiation and room temperature data are used as inputs in the numerical calculations. Between noon and two in the afternoon, as illustrated in Figure 2, the temperature difference between the evaporation surface of the liquid and the face of the condensing glass cover reaches its peak. Subsequently, it gradually diminishes throughout the day.

It is also worth noting the important temperature variation between the liquid and the surface of the glass cover in the basin containing the Copper scrap. Therefore, there is a linear relationship between the temperature difference midday and Productivity. Even during the peak solar light of the day, the water level in the basin remained low due to the slow dripping of salt water into it. Given that the water in the basin has a low thermal capacity, it increases production. Independent of the dripping setup, the energy storage materials are put through their paces. For 24 hours, the basin drip system continues to deliver 12 liters of salt water.

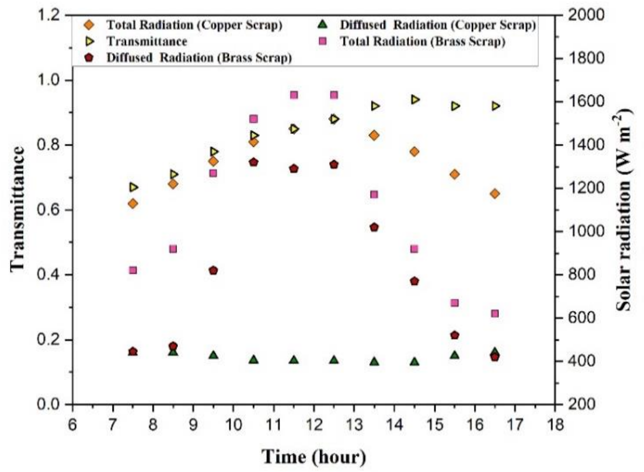


Figure 3. Difference of Solar Radiation and time with respect to time.

The transmission and diffuse radiation fraction are modified when glass is oriented toward the south (see Figure. 3). After analyzing the transmittance correlation reported by the authors (Bahiraei et al., 2021), it was concluded that the cover allowed for sufficient transmittance at all incident angles of solar energy. Glass covers facilitate the passage of a significant amount of light even when the solar angle is low, such as during the mornings and evenings.

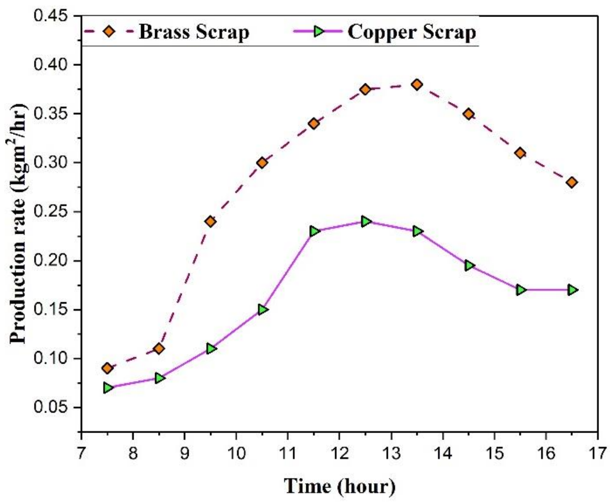


Figure 4. The production rate for energy storage materials.

Figure 4 displays the daily production rates of copper and brass scrap. Small, effective thermal storage materials were used thanks to a drip system that maintained a 1-cm water level in the basin, facilitating the collection of the required data. The findings indicate that employing Copper scrap as a storage medium enables the highest output rate to be maintained continuously throughout the day.

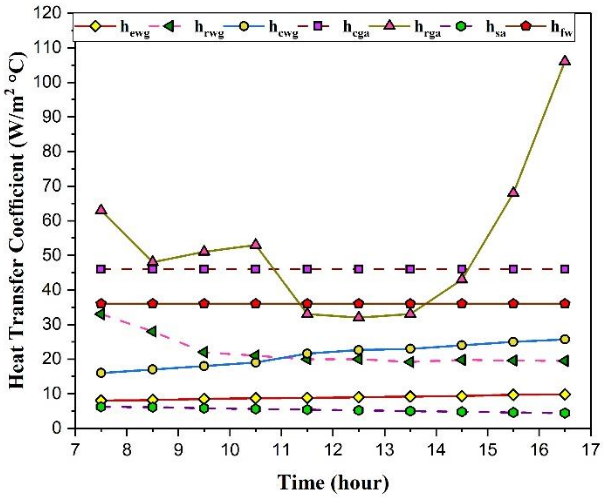


Figure 5. Difference in the average heat transfer coefficient

The internal and exterior heat transmission coefficients of solar still change throughout the day, as shown in Figure 5. Convection and thermal radiation exchange between the glass cover and the atmosphere have larger coefficients than other heat transfer processes inside the building throughout the day. Consequently, the saltwater used in the still exhibits a higher heat transfer coefficient than the still itself. This difference arises because, unlike the interior of the still, the exterior casing is always exposed to the elements.

Figure 6 displays the sum of output from a wide variety of plausible heat storage materials during the hours of 7:30 am and 4:30 pm. As can be seen from the graph, between 7:30 AM and 4:30 PM, the copper scrap in the basin generates more heat than any other sensible thermal storage material. After 24 hours of distillation, copper scrap is expected to yield 5.16 kg/m^2 of distillate. The nighttime production rate of 3.2 kg/m^2 can be attributed to the copper scrap in the basin.

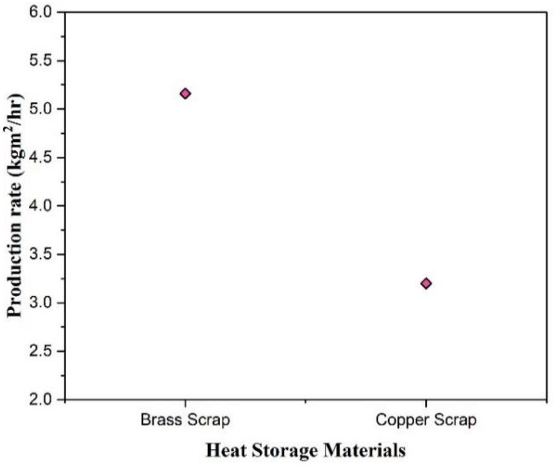


Figure 6. Comparison of Energy storage materials with Production rate.

Copper scrap has a higher heat capacity than any other material. The enhanced thermal conductivity of the scrap facilitates absorbing much solar heat during the day, thus increasing the distillate yield in the evening. The salt water is retained by the porous Copper scrap, and the energy in the water is utilized throughout the distillation process, even when the sun is not out or at night.

Based on the information provided, it appears that during May and June of 2022, tests were conducted on different sensible heat storage materials at consistent solar radiation levels. The consistent radiation levels observed across all days suggest that the tests were likely carried out under controlled conditions. This controlled environment enables accurate and reliable comparisons between the different materials being tested. When such days occur, it is reasonable to assume that the weather will be consistent with the usual conditions. Midday consistently exhibits the highest levels of solar energy, and this pattern repeats on a daily basis. Figure 7 illustrates the monitoring of daily changes in solar radiation and ambient temperature using different thermal storage materials.

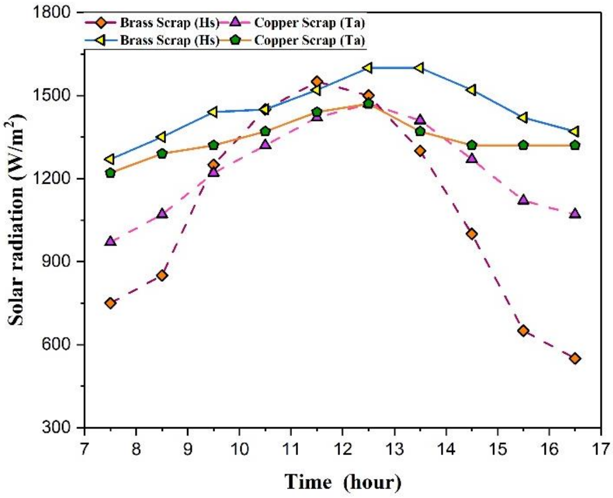


Figure 7. Difference between ambient temperature and solar radiation intensity.

A drop-free experiment with 1.8 cm salt water and Copper scrap was conducted. Figure 8 displays that adding a salty water basin with a dripper changes the output, water, and glass cover temperatures. As indicated by the graph, there is a significant temperature gradient between the water and the glass cover, which causes the evaporation rate to rise when a drop of salt water is generated using Copper scrap. Evaporation slows down because glass has a high thermal capacity, decreasing the temperature difference among the water and the surface. After 24 hours of dripping with copper scrap, distillate production increases by 36% compared to a saline basin.

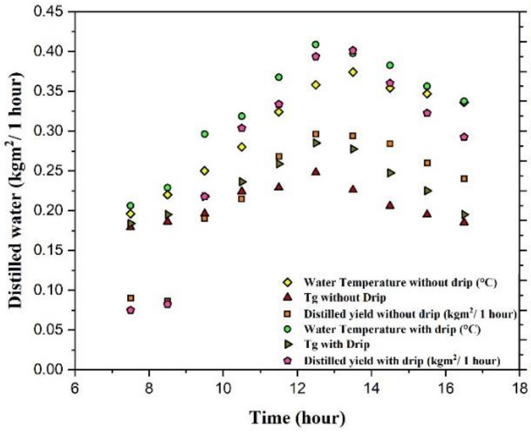


Figure 8. Variation of drip and drip-free factors

The basin cover glass temperature, water temperature, and copper scrap production rate are all depicted in Figure. 9 after a thorough examination. The experimental outcomes are in reasonable agreement with the theoretical predictions. Some experimental observations may deviate from the norm at specific points due to the projection of the basin's back and side walls, but these conditions are beyond the researchers' control.

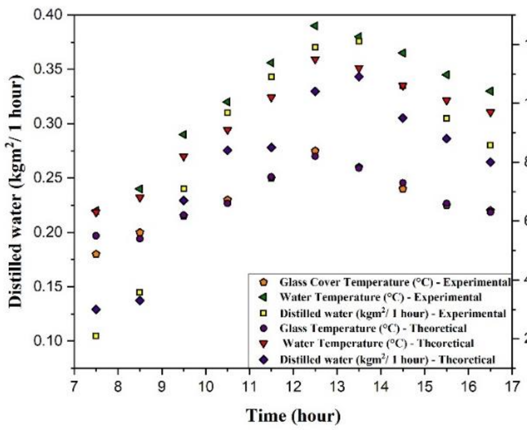


Figure 9. Comparison of theoretical and experimental data on water and glass cover.

The research paper refers to the diffusion process, which involves the movement of water molecules from areas of high concentration to regions of lower concentration, leading to the even dispersion of these molecules. In the context of a solar still, diffusion plays a crucial role in controlling the production of distilled water.

A typical solar still comprises a structure that captures sunlight, a basin that holds the water intended for distillation, and a sloping or angled condensing surface, often a transparent lid. When sunlight enters the still, it warms the water, causing it to vaporize. The resulting water vapor rises and meets the cooler condensing surface, which is usually cooler due to its position and thermal characteristics. As it touches the cooler surface, the water vapor transforms back into liquid droplets through the process of condensation.

In the case of the south-facing condensed cover mentioned in the research paper, the diffusion process is affected by several factors:

1. The production of distilled water is influenced by the temperature gradient that exists between the water vapor and the cooler condensing surface. A larger temperature difference results in a faster diffusion process, thereby increasing the rate of production of distilled water.
2. Surface properties of the south-facing condensing cover can have an impact on the diffusion process. Hydrophilic surfaces, which attract water, can accelerate the condensation process, while hydrophobic surfaces, which repel water, slow it down. Furthermore, the cover's transparency and thermal properties can affect the temperature gradient inside the solar still.
3. The rate of diffusion is influenced by the inclination angle of the south-facing condensing cover. A steeper angle can accelerate the process of condensation and runoff, thereby increasing the rate of production of distilled water. Conversely, a shallower angle may result in slower condensation and runoff, leading to a decrease in the production rate.

External factors such as air temperature, humidity, and wind speed can affect the diffusion process. For instance, higher air temperatures can augment the rate of water evaporation, while elevated humidity and wind speed have an adverse effect on the condensation process occurring on the cover.

Understanding the diffusion process in a solar still is essential to optimizing its performance. By carefully selecting materials, design, and operating conditions, it is possible to improve the efficiency of the solar still and increase the production rate of distilled water

5. CONCLUSION

(i) The theoretical modeling of the transfer and absorption of solar radiation through south-facing windows is explained, as well as the thermal efficiency of single-slope solar stills under typical conditions.

(ii) Copper scrap, with its high thermal mass and excellent heat retention properties, can be used to increase evaporation rates throughout the day and night.

(iii) In the presence of a copper scrap-containing basin, the thermal efficiency of the solar still is substantially increased due to the release of stored heat energy during periods of reduced solar radiation. Nonetheless, the high thermal capacity of the basin can adversely affect the overall production of the still when salt water is used. As salt water accumulates in the basin, the temperature difference between the condensing glass cover and the water beneath it increases due to the lower thermal capacity of salt water compared to fresh water.

The calculations indicate that the still has a total thermal efficiency of 71.3% and the results of the experiments support this finding. Additionally, the production rate is influenced by the diffusion process on the south-facing condensing cover, which in turn affects the temperature differential between the water, glass, and surrounding air.

6. ACKNOWLEDGEMENT

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NOMENCLATURE

PCM	Phase change material
SSSHSM	solar still using sensible heat storage material
CSS	Conventional solar Still
SSGC	Solar Still with only water dripping arrangemnt without
SSGCF	Solar still using glass cooling with water dripping and sisal fibers

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