

Integration of Phase Change Material and Heat Exchanger for Enhanced Solar Desalination – A Comparative Performance Investigation

Jothilingam Manickam[1] ✉ – Balakrishnan Nanjappan[1] – Nithyanandam Chandrasekaran[2]

1 Gnanamani College of Technology, India

2 Madha Institute of Engineering and Technology, India

✉ jothilingamm@gmail.com

Abstract *The performance and comparative analysis of several solar desalination systems using various configurations and materials are examined in this study. The study evaluates how these systems perform by measuring their overall productivity, temperature differentials, and thermal efficiency. A thorough assessment across a variety of characteristics was made possible by the consistent environmental conditions of the experiments. When phase change materials (PCM) were used as an energy storage medium, the overall amount of heat loss was significantly reduced. Studies comparing different solar stills revealed clear benefits, especially when using heat exchangers. Improved evaporative heat transfer coefficients, higher temperature differentials (ΔT), more usable heat absorption by the distilled water, and increased daily output were all seen in solar stills equipped with heat exchangers. The modified solar still with PCM and a heat exchanger had the best thermal efficiency, reaching 56 %, according to the results. The key objective of the research was to minimize heat losses and maximize freshwater yield. This thorough assessment and comparative study of several solar desalination systems offers insightful information for improving the productivity and efficiency of solar-powered water distillation technologies under a range of environmental circumstances.*

Keywords *solar desalination, phase change materials, efficiency enhancement comparative analysis*

Highlights:

- *PCMs reduced heat loss and improved thermal efficiency in solar desalination systems.*
- *Solar stills with heat exchangers showed higher output and better heat transfer.*
- *Heat exchanger integration maximized freshwater yield and minimized heat loss.*

1 INTRODUCTION

Energy conservation is vital for sustainability, especially in countries like India where resources are precious. Solar energy is renewable, it is essential to this endeavour. Solar stills demonstrate this importance by efficiently harnessing solar energy to purify water, offering a sustainable solution to address water scarcity while reducing dependence on conventional energy sources. Solar desalination is a method of separating clean water from seawater using solar energy, which is still an economical way to provide clean water. There are two categories of solar-assisted desalination systems: passive solar stills (conventional) and active solar stills (modified). Conventional solar stills consist a steel basin or black-painted copper that receives solar radiation and contains saline or seawater. In order to create a greenhouse effect and retain solar energy, the basin is encased in a trapezoidal wooden box with a glass cover at an angle of 10° to the horizontal. The glass wool insulation is packed between the basin and the wooden box to minimize heat loss. The air above the water surface gets saturated with water vapour equivalent to the water temperature because of the phase equilibrium between seawater and the air space. The surface temperature of the saline water increases when solar energy reaches it and leading to an increase in the water vapour's saturated pressure near the water surface as well as in line with the elevated temperature [1] to [3].

The partial pressure of water vapour at the glass surface lowers because of the temperature differential between the water and the inner surface of the glass cover, where the inner surface is cooler than the water surface. Condensation forms on the inside of the glass as a result of the water vapour moving from the water's surface to the glass's surface due to this difference in partial pressures. The rate of condensation inside the glass cover is directly influenced by the pace at which water vapour evaporates from the water's surface. The still per square meter aperture's average annual performance is usually restricted to 2.5 to 3 litres per day, even in areas with higher sun intensity. Traditional solar stills are popular because of their simple construction, economical running and maintenance costs, and usefulness in isolated locations without access to power. However, the limited production of these stills serves as a catalyst for academics to investigate and develop novel techniques targeted at enhancing their efficiency [4] and [5].

In the study of a solar still in Sultanpur, India, it was observed that reducing basin water depth increases yield due to quicker attainment of steady-state and early onset of evaporation. Additionally, increased wind speed positively influences yield by accelerating condensation, with minimal impact on basin mass temperature [6]. Soliman et al. [7] experimented a solar still with an integrated heat exchanger that was coupled to a solar collector in an experiment. It was discovered that a connected solar still can produce 2.75 times as much as a solitary solar still. It is estimated that the suggested still will operate at a total efficiency of 6.45 kg/m^2 half a day. A double slope active solar still experiment was conducted by Muhammadi et al. [8]. Next, the suggested heat exchanger's performance is contrasted with that of traditional stills, including serpentine and parallel channel heat exchangers. A heat exchanger with a unique design achieved the

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greatest efficiency of 39.4 %. Use of the NDHE results in a 34.1 % and 30.4 % increase in distillate production when compared to parallel channel and serpentine heat exchangers, respectively.

Fathy et al. [9] conducted an experiment using a parabolic trough collector and a dual slope solar still. It has been noted that a solar still equipped with parabolic trough collector (PTC) has a temperature that is higher than a standard solar still. Compared to a normal solar still, which produces roughly 28.1 % less fresh water, a solar still using PTC produces more. In an experiment, a solar still with an evacuated tube collector and thermoelectric module was used by Shafii et al. [10]. The study found that the use of forced convection improved the system's water yield and hourly efficiency, which peaked at 1.11 l/m^2 and 68 %, respectively. When the fan was removed from the system, the efficiency and water yield were reported to be 60 % and 0.97 l/m^2, respectively.

Divagar and Sundararaj [11] conducted an experiment using a solar distiller and a copper heat exchanger. A comparison was made between the energy efficiency of the modified and conventional solar stills. The modified still was found to have an energy efficiency of 28 %, while the conventional still had an energy efficiency of 17 %. A modified still's higher energy efficiency is 5.5 %, while a conventional still is 1.1 %. According to research by Nafey et al. [12], black rubber used as a storage medium within a single sloping solar still increases productivity by more than 20 % at the condition of 60 l/m^2 brine volume and 15° of a glass cover, respectively. Nafey et al. [13] investigated the effects of using a floating perforated black plate on two experiment still units, each measuring 0.25 m^2. Studies show that exposure to sunlight increases production by 15 % at 3 cm brine depth and 40 % at 6 cm brine depth.

According to research by Akash et al. [14], employing various absorbing materials, such as black rubber mats, enhanced daily water productivity by 37 %, 45 %, and 60 % when combined with black ink and black dye. El-Sebaii et al. [15] explored methods to reduce the time required for the water in the basin of a solar still featuring a baffle-hung absorber to heat up. The addition of the baffle absorber results in a 20 % increase in productivity compared to a conventional solar still without baffles. Bassam and Rababah [16] conducted research using sponge cubes of varying sizes submerged in a basin. In comparison, a similar still without sponge cubes, increased by 18 % to 273 %. Rahim [17] suggested a novel way to store additional heat energy in a horizontal solar still throughout the day in order to forward the research. By segmenting the horizontal still into discrete zones for heat storage and evaporation, this technique stores more than 42 % of the overall energy during the night-time.

As explained in Tamini [18] research, functioning under various conditions with and without a reflector and black box still significantly increased productivity. According to research by Badran [19], the output of a still might rise by up to 51 % when coupled enhancers like sprinklers and asphalt basin liners were applied to the still. Using absorbent materials like cotton & jute fabric, sponge sheet, and natural rock. Murugavel et al. [20] conducted research, in comparison with other materials, cotton fabric yields higher productivity. According to research by Tripathi and Tiwari [21], the storage effect causes a greater yield to be produced during the off-peak hours when compared to higher water depths. Many researchers have tried in vain to speed up the rate at which water evaporates and to maximize the quantity of solar radiation that strikes the still in order to improve system efficiency and use the least amount of still surface. This study introduces a novel approach by integrating phase change material (PCM) to reduce heat loss in solar desalination systems. Through extensive experimentation and comparison, the study extends the boundaries of solar desalination technology to identify the most efficient configuration.

2 EXPERIMENTAL

2.1 Setup

In this experiment, there are two solar stills installed at Vellore, Tamil Nadu, India. It is fixed to see how well this function in actual operating environments. The basin liner made up of galvanized iron sheet and the basin surface are painted with black paint to absorb maximum amount of solar radiation incident on them. It was intended the 4mm-thick glass condenser surfaces to be as heated- absorbing, as light-reflective, as solar-letting as feasible, and as resistant to heat loss as possible. For this reason, the surfaces were angled at a 10° angle. There is a wood used to frame the glass coverings and silicon rubber to seal them in order to keep everything together. Because it permitted expansion and contraction between the different materials, this seal was extremely crucial. The specifications for the glass cover included absorption of heat, low solar reflectance, maximum solar penetration, and exceptional heat retention in the basin. In order to assess how well these stills worked, it was handled carefully to document every detail of the experiment, including the temperatures and the amount of water we generated.

In the setup, condensed distillate that collects on the interior surfaces of the glass covers is collected in the setup utilizing a galvanized iron (GI) sheet collecting trough inside the solar still. This trough efficiently directs the condensate into a designated collecting flask. To accurately measure the water depth, a steel rule is securely fastened along the inside wall of the setup. Furthermore, thermocol and wood layers are used as insulation on the sides and bottom to reduce heat loss. Table 1 contains comprehensive technical details about the solar still, and Fig. 2 shows the experimental setup.

Table 1. Technical specification of the solar still

Specification	Dimension
Basin liner	0.5 m^2
Glass area	0.508 m^2
Glass thickness	4 mm
Number of glass sheets	1
Slope of glass	14^0
Thermocol thickness	25 mm
Thermal conductivity of thermocol	0.015 W/(mK)
Wood thickness	12.5 mm
Thermal conductivity of wood	0.055 W/(mK)

Fig. 1 showcases various pictorial views of the absorbing materials used in the setup, highlighting their specific placements and configurations. Moreover, Fig. 3 presents a snapshot providing a visual depiction of the experimental arrangement, offering an insight into the overall setup and components in use.

The trials were carried out in May of 2022 in order to record normal conditions characteristic of that season. Three separate days were used for these trials in Vellore, India. The material used to store energy was wax, which kept in copper tubes. This PCM released heat when it wasn't in the sun and absorbed it during the day. Every experiment ran for twenty-four hours, starting at nine in the morning local time. During each experiment, a consistent water depth of 1 cm was kept. Before beginning the next experiment with a new absorbing material, the apparatus had to sit idle for at least one day in order to guarantee uniformity and establish a steady-state condition while switching between different absorbing materials.

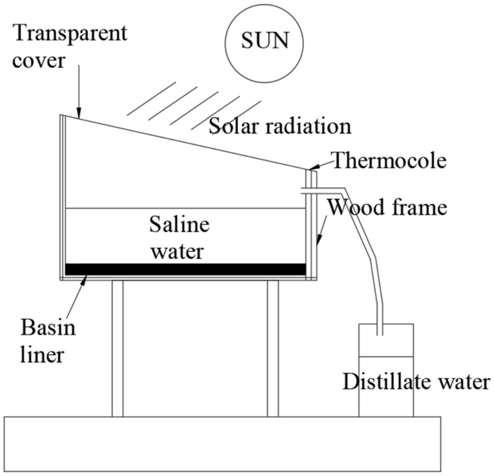

Fig. 1. Schematic diagram of experimental setup

This interval of inactivity continued from the end of the preceding trial until the current absorbing material experiment started. Keeping the water depth and inclinations constant, the following dynamic parameters were measured hourly over the course of a day: air velocity, solar radiation, distillate output, and many temperature measurements for the basin, back wall, side wall, water, glass, moist air, and ambient temperatures. K-type thermocouple combined with a digital indicator with a resolution of 0.1 °C were used to measure the water, basin, glass, and vapour temperatures. A pyranometer was utilised to measure solar radiation, and a digital anemometer was employed to monitor wind velocity. 30 mm steel rule is fixed in the inside wall of solar still to measure water depth. And the readings are shown in Tables 2 and 3.

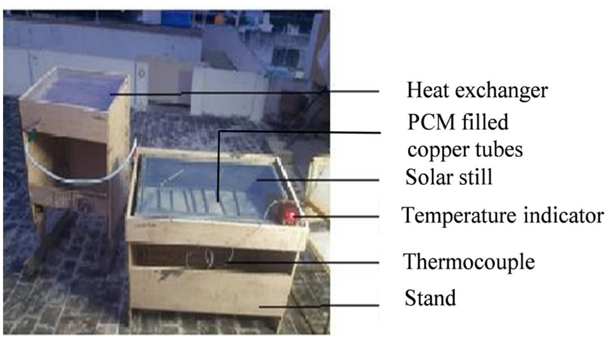

Fig. 2. Experimental setup

3 THERMAL ANALYSIS OF SOLAR STILL

The performance thermal analysis is achieved through an energy balance of the still. The energy transfer mechanisms for various components of the still, which significantly influence the output, are illustrated in Fig. 3.

To simplify the analysis, the following assumptions are considered:

- The water level in the basin remains constant throughout.
- Condensation at the glass trough occurs in a film-like manner.
- Negligible difference exists in the heat capacity among the absorbing material, insulating material, and the glass cover.
- No vapour leakage transpires within the still.
- The insulator's heat capacity, both at the bottom and sides of the still, is assumed to be negligible.

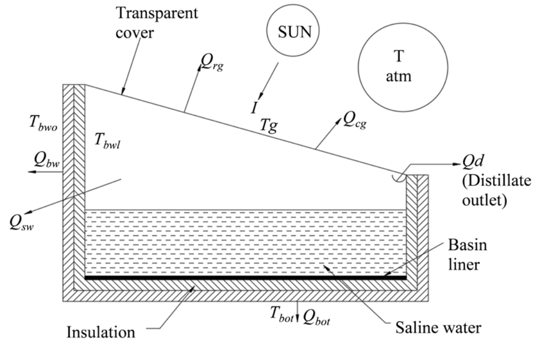

Fig. 3. Various components of conventional single slope solar still

By formulating an energy equation for a solar still and referencing Fig. 1, the still's collecting efficiency can be determined.

$$I \cdot a_g = \dot{Q}_d + \dot{Q}_{rg} + \dot{Q}_{cg} + \dot{Q}_{bw} + \dot{Q}_{sw} + \dot{Q}_{bot}, \quad (1)$$

where I is the hourly incident solar radiation, a_g is exposed glass surface area, $\dot{Q}_d$ is the heat flow rate needed for water distillation, $\dot{Q}_{rg}$ is the thermal radiation heat loss from the glass to the ambient $\dot{Q}_{cg}$ is the convective heat transfer from the glass to the ambient, $\dot{Q}_{bw}$ is the heat loss through the rear wall from inside to outside, $\dot{Q}_{sw}$ is the heat loss through the sidewall from inside to outside and $\dot{Q}_{bot}$ is the rate of heat transfer from the basin liner to the atmosphere through the bottom wall.

The Eq. (2) for $\dot{Q}_d$ is

$$\dot{Q}_d = \dot{m}_w \cdot h_{fg}, \quad (2)$$

where $\dot{m}_w$ is the mass flow rate of distilled water output, and h_{fg} enthalpy of vaporization of water (h_{fg} = 2382 kJ/kg). The convection from the glass to ambient is defined as

$$\dot{Q}_{cg} = h_{cg} \cdot a_g \cdot (T_g - T_a), \quad (3)$$

where h_{cg} is the convection coefficient amidst the glass and ambient surroundings, a_g is area of glass, T_g is temperature of glass and T_a is the temperature of ambient. Convection coefficient is primarily reliant on velocity of the wind, given by the empirical expression

$$h_{cg} = 5.7 + 3.8\,V, \quad (4)$$

where V is the wind velocity.

The thermal radiation from glass to the ambient surroundings equals to

$$\dot{Q}_{rg} = \varepsilon_g \cdot a_g \cdot \sigma \cdot (T_g^4 - T_s^4), \quad (5)$$

where ε_g is the emissive coefficient of the glass material, σ Stefan Boltzmann constant (5.67×10^{-8} W/(m²·K⁴)), a_g is exposed glass surface area, and T_s is a temperature of the sky, which is lower than the surrounding air.

$\dot{Q}_{bw}$ is heat transfer through the rear wall from inside to outside

$$\dot{Q}_{bw} = a_{bw} \cdot U \cdot (T_{bwi} - T_a), \quad (6)$$

where a_{bw} is the area of back wall, and U is overall heat transfer coefficient.

Heat transfer through the side wall from inside to outside is equal to

$$\dot{Q}_{sw} = a_{sw} \cdot U \cdot (T_{swi} - T_a), \quad (7)$$

where a_{sw} is side wall area.

$\dot{Q}_{bot}$ is the rate of heat transfer from basin liner to atmosphere through bottom wall, and expressed by conduction equation of composite wall, defined as

$$\dot{Q}_{bot} = a_b \cdot U \cdot (T_b - T_a). \quad (8)$$

Finally, the thermal efficiency η is

$$\eta = \dot{Q}_d / \Sigma\dot{Q} \cdot 100. \quad (9)$$

4 RESULTS AND DISCUSSIONS

Without using any absorbing material, readings in a range of temperatures across a range of time periods have been tabulated. Through the use of an anemometer, the wind velocity was measured. K-type thermocouples were used in conjunction with a digital temperature gauge to record the water, basin, glass, and vapour temperatures.

4.1 Comparison of Energy Distribution Percentages

The energy balance equation yields heat loss, which derived from Eqs. (2) to (8). Because the modified solar still with PCM is more productive at producing fresh water than the basic solar still with PCM, it is clear that the energy consumption for freshwater conversion ($\dot{Q}_d$) is much higher in the modified sun still. As a result, less distilled water is produced during times when there is no sunshine.

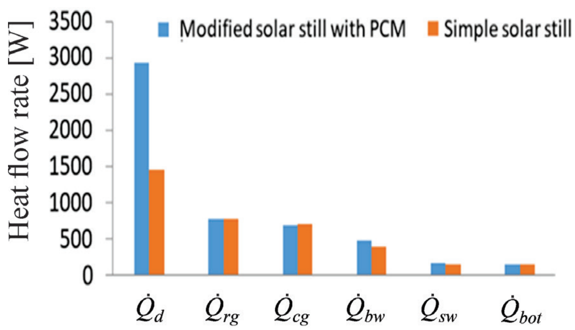

Fig. 4. Comparison of percentage of energy distribution

Furthermore, a combination of radiation and convection factors causes the main source of energy dissipation from the still to happen at the glass surface. On the other hand, due to the extensive insulation, heat losses through the side wall, back wall, and basin liner are negligible. The addition of PCM to the basin liner's bottom as an energy storage material improves its insulating performance. As a result, when considering the other aspects of energy distribution, the heat loss at the bottom wall for the modified and simple solar stills is 139.6 W and 137.8 W, respectively. When compared to the basic solar still with PCM, the improved performance of the modified solar stills with PCM shows a 49.02 % improvement. Fig. 4 shows comparison of percentage of energy distribution.

4.2 Comparison of ΔT (Temperature difference) for Modified and Simple Solar Stills Equipped with PCM

One important component affecting a solar still's production is its ΔT. A higher ΔT indicates a higher level of productivity from the solar still. Fig. 5 shows the temperature differences between the water and glass for several solar still types.

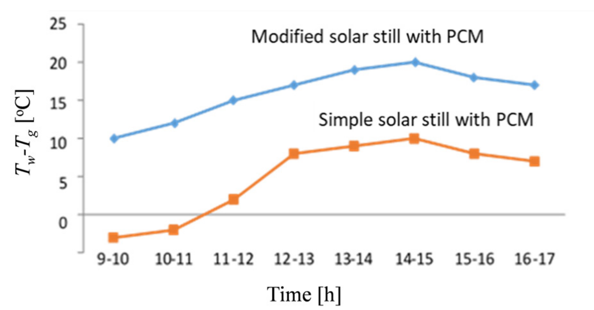

Fig. 5. Comparison of ΔT of modified and simple solar still having PCM

Table 2. Simple solar still with PCM

Sample number	Time	I [W/m²]	T_{bi} [°C]	T_{si} [°C]	T_b [°C]	T_w [°C]	T_g [°C]	T_a [°C]	Mass [l/m²]	Wind velocity [m/s]
1	09-10	490	33	32	31	27	30	24.7	0.00	0.04
2	10-11	607	35	33	33	33	35	28.3	0.09	1.1
3	11-12	715	46	45	43	50	48	31	0.25	0.07
4	12-13	895	51	50	48	60	52	33	0.33	0.06
5	13-14	845	64	64	60	75	69	36	0.45	0.05
6	14-15	790	69	67	65	80	72	33	0.5	0.07
7	15-16	680	65	65	63	77	69	29	0.3	1.2
8	16-17	510	59	58	55	70	63	27	0.25	0.03
	17-09								0.90	
Total									3.07	

Table 3. Modified solar still with PCM

Sample number	Time	I [W/m²]	T_{bi} [°C]	T_{si} [°C]	T_b [°C]	T_w [°C]	T_g [°C]	T_a [°C]	Mass [l/m²]	Wind velocity [m/s]
1	09-10	495	43	40	35	45	35	25	0.09	0.05
2	10-11	603	47	45	37	50	38	29	0.18	1.2
3	11-12	720	53	51	45	63	48	32	0.53	0.08
4	12-13	889	59	60	48	72	55	35	0.65	0.06
5	13-14	853	69	63	59	87	68	36	0.88	0.07
6	14-15	793	71	69	63	89	69	34	1.01	0.08
7	15-16	685	65	64	60	85	67	31	0.57	1.3
8	16-17	520	61	60	58	80	63	29	0.5	0.02
	17-09								1.82	
Total									6.23	

A considerably larger temperature differential between the water and the glass is seen in the modified sun still with a phase change material (PCM) and a heat exchanger than in the standard solar still with PCM. By allowing the water to be heated before it enters the still, this improvement significantly improves the performance of the modified solar still. Furthermore, it is clear that the ΔT for the basic solar still varies, rising in the afternoon and falling somewhat in the morning. Due to increased heat transfer between the water and glass, both sun stills show a very high ΔT around the 13-hour mark.

4.3 Comparison of Water Mass Productivity Among Different Solar Stills

The use of storage materials plays a key role in storing more energy in the form of sensible and latent heat. This results in a lower temperature rise of the water surface, thereby delaying the occurrence of maximum hourly yield. Significantly, a notable output is seen the next day, which increases production as heat trapped in stills with storage materials is released from 5 pm to 9 am.

The hourly productivity comparison of different solar stills is shown in Fig. 6. The addition of energy storage materials and a heat exchanger significantly increases the modified solar still's daily output. This improvement is ascribed to a greater ΔT and the distilled water absorption of usable heat ($\dot{Q}_d$). As a result, the improved solar still's performance improvement hits 49.27 %, outperforming the basic solar still with PCM.

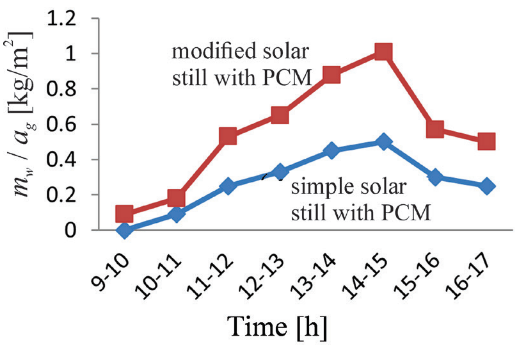

Fig. 6. Comparison of hourly productivity for various still

4.4 Comparative Efficiency Analysis of Various Solar Stills

The efficiency comparison of several types of solar stills is shown in Fig. 8. With a 56.75 % efficiency rating, the adapted solar still showed the best performance among them. When compared to the basic solar still, the upgraded solar still's average performance increase was a staggering 71.01 %. The significant enhancement can be ascribed to the elevated ΔT and the distilled water's absorption of usable heat ($\dot{Q}_d$). Fig. 7 shows Comparison of efficiency of different solar still.

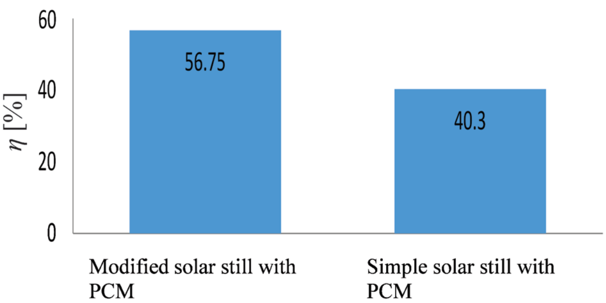

Fig. 7. Comparison of efficiency of different solar still

The combination of a heat exchanger and PCM in the solar still helps to increase the ΔT and $\dot{Q}_d$ while decreasing total heat loss, which results in increased yield. The total efficiency of the system is improved as a result of this all-encompassing approach.

5 CONCLUSIONS

The study of the solar desalination system is based on the thermal efficiency, determined by Eqs. (1) and (9). The experimental trials were carried out, covering a thorough investigation of several factors such as the temperatures of the basin water, the glass cover, the hourly yield, the back and side internal wall temperatures, and the bottom surface temperatures. The trials were conducted under the same climate to provide a comprehensive and equitable analysis for comparison reasons. Notably, in all cases, the energy consumption for the manufacture of distilled water ($\dot{Q}_d$) peaks around three o'clock. The use of PCM as a storage material successfully lowers heat loss overall. When compared to the basic solar still, the improved solar still has a greater thermal efficiency.

Throughout the trials, it was observed that heat losses through the bottom ($\dot{Q}_{bot}$) and side walls ($\dot{Q}_{sw}$) to the surrounding air remained constant, gradually increasing over time. The utilization of energy-storing materials facilitated significant heat release during periods of reduced solar intensity, thereby sustaining production levels during late afternoon and night-time. Among the designs evaluated, the solar still equipped with a heat exchanger demonstrated superior performance, attributed to its higher daily output (m_w), elevated ΔT, enhanced evaporative heat transfer coefficient, and increased absorption of usable heat by distilled water ($\dot{Q}_d$). Consequently, overall heat losses were reduced, leading to an enhanced efficiency of 56 %. In summary, the integration of a heat exchanger with the solar still emerges as the most effective approach for freshwater production, offering optimal efficiency and performance.

NOMENCLATURES

I	hourly incident solar radiation, [W/m²]
$\dot{Q}_d$	heat flow rate for water distillation, [W]
$\dot{m}_w$	mass flow rate of distilled water output, [kg/s]
h_{fg}	enthalpy of vaporization of water, [kJ/kg]
$\dot{Q}_{cg}$	convection heat transfer from the glass to ambient, [W]
h_{cg}	convection heat transfer coefficient, [W/(m²K)]
a_g	exposed glass surface area, [m²]
T_g	temperature of the glass, [°C]
T_a	ambient temperature, [°C]
V	wind velocity, [m/s]
$\dot{Q}_{rg}$	thermal radiation from glass to ambient, [W]
ε_g	emissivity of the glass, [-]
σ	Stefan-Boltzmann constant, [W/(m²K⁴)]
T_s	sky temperature, [°C]
$\dot{Q}_{bw}$	heat transfer through the rear wall, [W]
a_{bw}	rear wall area, [m²]
U	overall heat transfer coefficient, [W/(m²K)]
T_{bwi}	inside temperature of the rear wall, [°C]
$\dot{Q}_{sw}$	heat transfer through the side wall, [W]
a_{sw}	side wall area, [m²]
T_{swi}	inside temperature of the side wall, [°C]
$\dot{Q}_{bot}$	heat transfer through the bottom wall, [W]
a_b	bottom wall area, [m²]
T_b	basin liner temperature, [°C]
η	thermal efficiency, [%]

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Uporaba fazno spremenljivih materialov in prenosnika toplote za izboljšano solarno razsoljevanje - Primerjalna raziskava učinkovitosti

Povzetek *V tej študiji sta preučena delovanje in primerjalna analiza več solarnih sistemov za razsoljevanje z uporabo različnih konfiguracij in materialov. Študija obravnava delovanje teh sistemov z merjenjem njihovega splošnega delovanja, temperaturnih razlik, zmogljivosti shranjevanja energije in toplotne učinkovitosti. Temeljito oceno različnih značilnosti so omogočili dosledni okoljski pogoji poskusov. Pri uporabi fazno spremenljivih materialov (PCM) kot medija za shranjevanje energije se je skupna količina toplotnih izgub znatno zmanjšala. Študije, v katerih so primerjali različne sončne peči, so pokazale očitne prednosti, zlasti pri uporabi prenosnikov toplote. Izboljšani koeficienti izhlapevanja, večje temperaturne razlike (ΔT), večja absorpcija uporabne toplote v destilirani vodi in večja dnevna proizvodnja so bili opaženi pri sončnih pečeh, opremljenih s prenosniki toplote. Glede na rezultate je imel spremenjeni solarni destilator s PCM in prenosnikom toplote najboljšo toplotno učinkovitost, ki je dosegla 56 %. Ključni cilj raziskave je bil čim bolj zmanjšati toplotne izgube in povečati donos sladke vode. Ta zasnova se je izkazala za najuspešnejšo metodo za pridobivanje sladke vode. Ta temeljita ocena in primerjalna študija več solarnih sistemov za razsoljevanje vode ponuja pomembne informacije za izboljšanje produktivnosti in učinkovitosti tehnologij za destilacijo vode na sončni pogon v različnih okoljskih okoliščinah.*

Ključne besede *solarno razsoljevanje, fazno spremenljivi materiali, primerjalna analiza povečanja učinkovitosti*