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Water Desalination Using PCM to Store Solar Energy

Paritosh Kulkarni

Abstract

The rising water pollution levels and depleting freshwater sources have formed a delirious inverse proportionality for which the cause is human and effect is also on humanity. A possible solution to this problem is harnessing solar energy to engender thermal energy for solar distillation. Thus solar distillation is one of the potential solutions to assess both the ever-increasing demands for clean water and the inquisition for finding eco-friendly techniques to yield the water. This analysis was undertaken to discover the possible utilization of phase change material on solar distillation in double-slope solar still. The equipment that performs distillation is called “Solar Still.” A phase change material (PCM) is a substance that either releases or absorbs energy comparable to the sensible heat during its phase transition to provide useful heat/cooling. Examples of PCM include phenol, paraffin, salt hydrate, and fatty acid. The experiment includes a blank distillate output without PCM, followed by possible optimization on the designed solar still. Solar distillation was performed in the improved solar still with varying types of PCMs. A theoretical model discerning the above phenomena and experiments were performed on the solar still. It was reported that for the yield maximum of water distillate with PCM (Phenol—5 cm) is 370 mL and without PCM is 345 mL, showing a 7.2% increase.

Keywords: solar still, phase change material, phenol, sustainability, water-desalination, renewable energy

1. Introduction

In recent years the energy shortage and water pollution have been rising around the world. With the rapid increase in the level of greenhouse gas emissions, the discovery of alternative sources of energy is increasingly gaining importance for the development of a sustainable world. The rising oil price and environmental regulations have dramatically increased the demand for utilizing alternative power sources [1]. In 2015 WHO and UNICEF reported that around 663 million people still use non-potable drinking water. During the emergency conditions, the need for developing efficient and portable techniques to obtain a clean source of water is paramount. One such method is solar distillation using phase change material.

In the twenty-first century, the impact of energy and water on the socioeconomic development of developed and developing nations is significant [1]. Solar energy is one of many renewable energy sources to obtain stable thermal energy

future generations [2]. The process of distillation can be used to get fresh water from brackish or contaminated water. Water is available in different forms, such as seawater, underground water, surface water, and atmospheric water. Clean water is essential for good health. These current conditions serve as a motivational factor for the research conducted, to effectively use Phase Change Material for optimum solar distillation to desalinate the water, abundant in situ around Udupi (near the Indian Ocean) [3].

Single/double-slope solar still is a popular solar device used for converting available brackish or wastewater into potable water. Solar still absorbs the thermal energy solar radiation to distillate polluted water into potable water in an enclosed space—still. The principles of heat transfer and energy balance were the governing equations for the operation of single-slope solar still. Because of its lower productivity, it is not popularly used. Numbers of works are undertaken to improve the productivity and efficiency of the solar still [2, 4].

Several PCMs melt and solidify at an array of temperatures, thus creating a focus on various possible applications. These PCMs are applied for numerous thermal storage systems utilizing latent heat, applications in heat pumps, engineering using solar radiation, and space travel. PCMs have been used for heating and cooling for many years, and the study in this regard has been attracting attention since the past decade. The pragmatic results reckoned in the field of water distillation process with the help of solar energy in the presence of energy storage materials like water and MOFs [2, 5].

Solar still is a latent heat storage system, which uses phase change materials (PCMs). Using PCM is an impactful way of storing thermal energy and has benefits in terms of high-energy storage density and the isothermal nature of the storage process. PCMs have been widely used in latent heat thermal-storage systems for heat pumps, solar engineering, and spacecraft thermal control applications. There are large numbers of PCMs that melt and solidify at a wide range of temperatures, making them attractive in a number of applications [6].

The desalination can provide a 24-hour supply of heat and water in greenhouse-based agricultural projects [7]. In another unsteady state modeling and simulation approach, El-Sebaai and his co-authors presented the transient mathematical models for a single-slope single-basin solar still with and without phase change material under the basin liner [3, 8]. They used stearic acid as PCM and used a computer-based simulation procedure to obtain a better insight of temperatures of the still elements and the PCM. The data were correlated using summer and winter day's temperature data in Jeddah, Saudi Arabia. It was observed that during phase change (liquid to stable) of PCM, the convective heat transfer coefficient from the basin liner to basin water is doubled; thus, the evaporative heat transfer coefficient is increased by 27% upon using 3.3-cm layer of stearic acid beneath the basin liner. Dashtban [9] used paraffin wax as PCM in their theoretical study of PCM-based weir-type cascade solar still. It was expected to obtain enhanced productivity by using PCM, which helps in keeping the temperature of basin high enough to produce the distilled water without interruption, especially after sunset [10]. In this study, water desalination and hot water production using solar still involving PCM are theoretically investigated. The numerical approach is presented to study the performance of desalination units—with and—without phase change materials. The effect of the PCM on the productivity expressed as the amount of water produced is theoretically studied. The following parameters and their effects were theoretically investigated: the type of the PCM, melting point of PCM, solar irradiation. It is hoped to determine the optimum parameter that will result in higher unit productivity. The purpose of a solar distillation system is to clean or purify water within the permissible limit [11, 12]. Besides the

problem of water shortage, process energy constitutes another problem area. Due to the high cost of conventional energy sources, which are also environmentally harmful, renewable energy sources have gained more attraction since their use in distillation plants will save conventional energy for other applications, reduce environmental pollution and provide a free, continuous, and low maintenance energy source [13].

The objective of this thesis is to study how solar distillation is used by nature to produce rain, which is the primary source of freshwater supply and replicate the process using knowledge of engineering. Solar radiation falling on the surface of the sea is absorbed as heat and causes evaporation of the water. The vapor rises above the surface and is moved by winds [7]. When this vapor cools down to its dew point, condensation occurs, and freshwater precipitates as rain. All available artificial distillation systems are small-scale duplications of this natural process.

Solar distillation differs from other forms of desalination that are more energy-intensive, such as methods such as reverse osmosis, or simply boiling water due to its use of free energy. A very common and, by far, the most significant example of solar distillation is the natural water cycle that the Earth experiences [4].

The novelty of the present study is an in-depth and multifaceted comparison of two solar distillation methods, that is, one utilizing PCM to discover an effective way to bring about solar distillation and another technique reflecting the natural phenomenon of distillation. Two methods can accompany the distillation of water using solar energy. The first method utilizes the so-called greenhouse effect to evaporate saltwater enclosed in a simple solar still (direct collection). A typical basin type containing the saline water is covered with a transparent airtight top. The top is mounted sloping downward toward sweet water collecting troughs. Solar energy is absorbed by the basin, causing the water to evaporate and condense on the inside of the cover and slides down into the collecting trough. The second method or indirect collection system often involves more than one subsystem, one for collecting and another for energy storage and the third system for energy utilization in the distillation process, multi-stage flash evaporation may offer good potential when utilized in a solar distillation system [6].

To emphasize the scope of this research, consider rural areas in and around Udupi district and several such underdeveloped regions around the tropic of cancer. In these areas, the solar distillation process yields drinking water tantamount to the process of rain generation in the water cycle. The solar radiation causes water to evaporate, segregating the water vapor from salt or impurities. The vapor formed from the process of evaporation condenses on the still for collection [14]. The fundamental operation is evaporation. As the temperature of water increases, vaporization starts at the surface of the liquid. The vapor then rises from the surface of the water and gets condensed on the top cover. The condensed vapor is free from minerals and impurities and thus separated through some distillate channel [15]. The application of finding from this thesis encompasses solar energy applications, primarily supported by government initiatives in the countries along tropic of cancer, including India, Mexico, and UAE.

We are choosing two heights—5 and 7 cm— of PCM to understand and relate this distillation over real application in salt pans. The average height of human-made salt pans near the coast of Karnataka is in the range of 25 cm. Since the height of PCM is less than the height of the salt pan, its implementation is possible. If implemented, this method of distillation can obtain not only potable water but also residue salt [16]. The 2-cm increment is to study the effect.

Figure 1 below represents the solar still to be designed as intended, upon which experimental work has been performed to yield the results as presented below.

Figure 2 represents the schematic of that implementation. The angle of Glass Cover is kept at 32° following the laws of reflection and refraction, to explain that let us consider Snell's law of refraction and law of reflection.

Figure 1 schematic is a focused view of glass cover in **Figure 2**, say $\mu_2 = 1.003$ and $\mu_1 = 1.517$ are refractive indices of air and glass cover [17];
we have,

$$\mu_1 \times \sin \theta_2 = \mu_2 \times \sin \theta_1 \tag{1}$$

And so assuming all rays are incoming perpendicular, thus,

$$\sin \theta_1 = 1,$$

we get

$$\theta_2 = \sin^{-1}(\mu_2/\mu_1) = 41.14^\circ, \tag{2}$$

which is the ultimate critical angle of the glass cover, and the angle we chose is 32° signifying maximum refraction [4].

Giving as of **Figure 1**, say we have $\theta_1 = 32^\circ$ and $\theta_2 = 58^\circ$

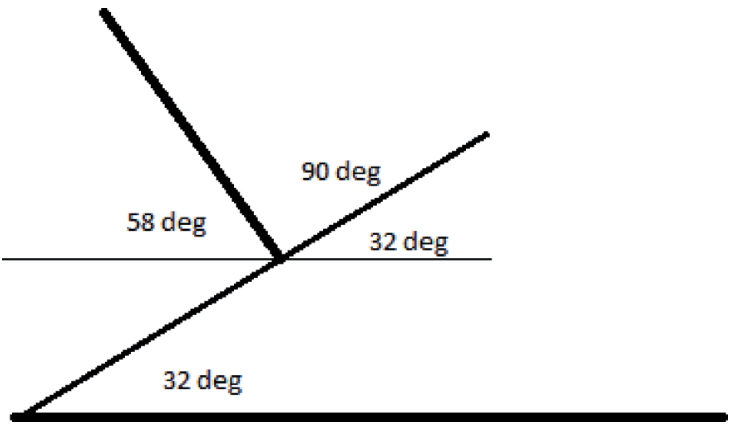


Figure 1.
Schematic of glass cover and sunrays.

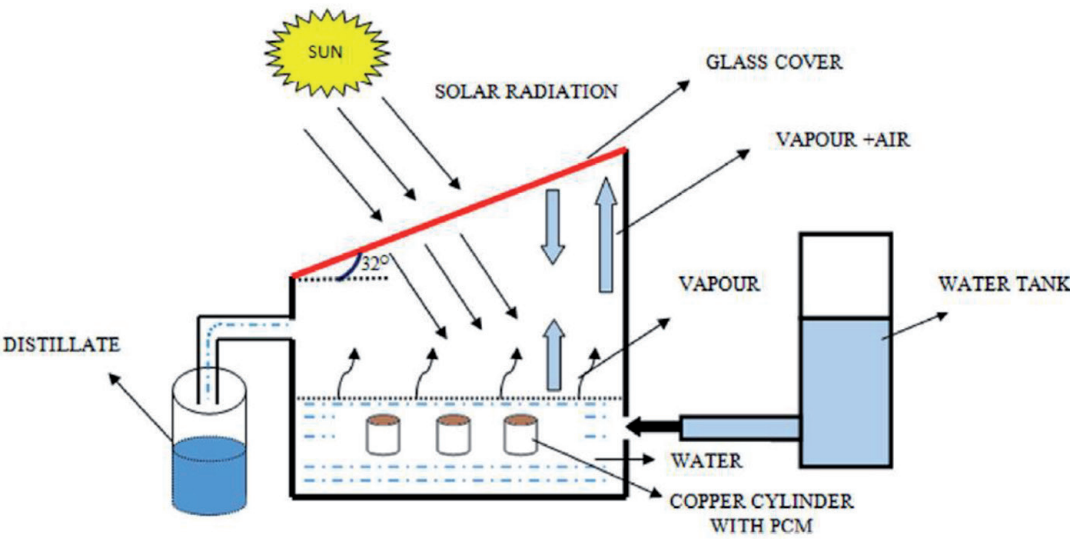


Figure 2.
Solar distillation still with PCM: schematic [4].

2. Methodology

2.1 Materials

Figure 3 shows PCM classified according to their commonalities as per the melting point and the enthalpy of fusion. It follows that the two vital characteristics of phase change material, relating to their semantics “phase” and “change,” are derivatives of temperature and heat released during the phenomenon of phase change [18, 19].

In this pragmatic study, the experimental setup is similar to the one described in **Figure 1**, and the following phase change material was used:

- Water and water solutions with eutectic compositions are used below the triple point [5].
- Phenol.

As we can observe in **Figure 2**, both of these compounds are on the left corner of the graph with melting temperature near zero or below zero and enthalpy of fusion around 300 MJ/m³. Hence, the comparison is rather challenging owing to the similarities between the two compounds [20].

As far as the solar distillation goes, the following **Figure 4** summarizes the various substances used for an optimized solar distillation setup. Each material novel and being researched upon [14].

2.2 Experimental synopsis

2.2.1 Experimental setup

Double-slope solar still shown schematically in **Figure 5** was used to conduct the experiments [21]. Concerning **Figures 1** and **2**, we have designed this schematic

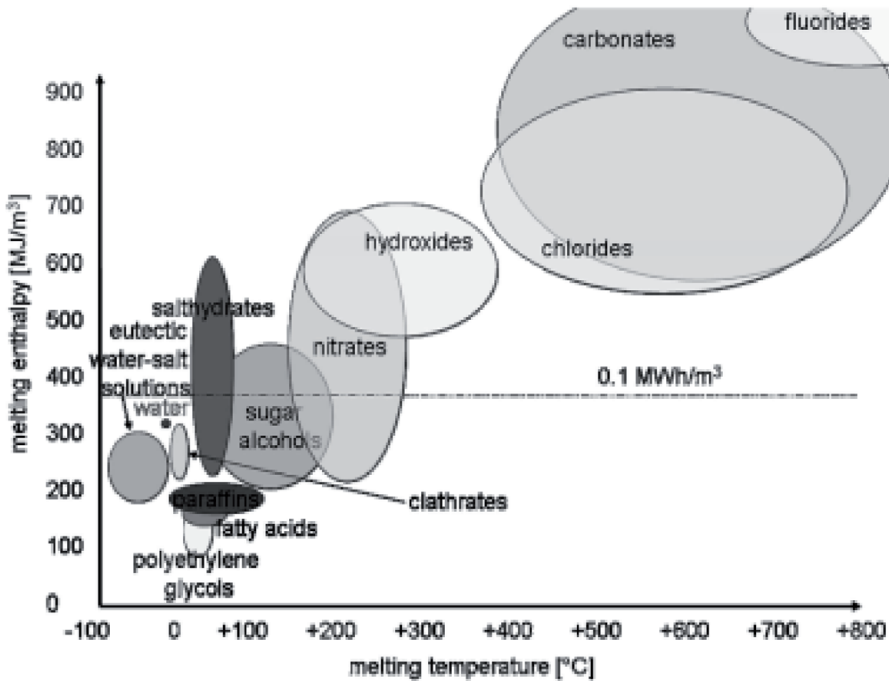


Figure 3.
Classes of materials that can be used as PCM and their typical range of melting temperature and melting enthalpy [15].

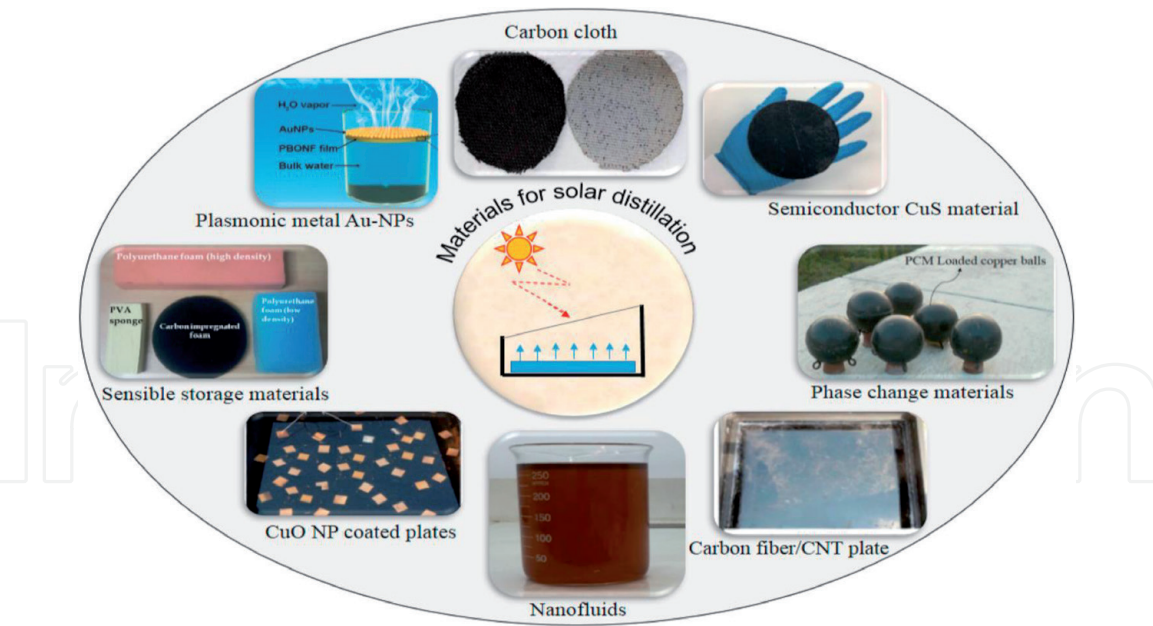


Figure 4.
Various materials used for solar distillation [3].

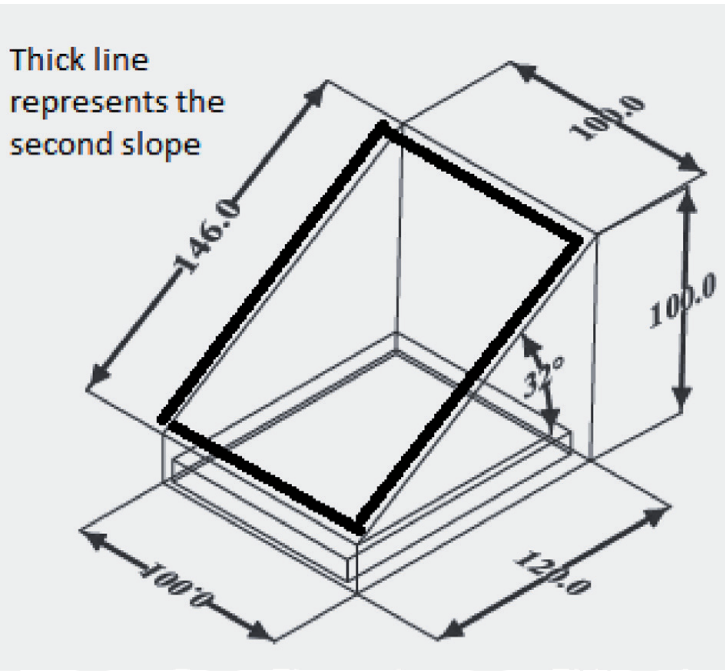


Figure 5.
Schematic of double-slope solar still measurements in cm.

with lines of varying strokes and measurements of solar still that we implemented for real-time experiments.

As shown in **Figure 5**, the base or basin of double-slope solar still was made using an 18-mm-thick waterproof plywood obtained from a local vendor marking the instance of the in situ experimental setup. The side walls were constructed using the same 6-mm thick plywood. The solar basin had an approximate active area (A) of 0.9 m². The inside of still was coated with waterproofing M-Seal an epoxy compound with a resin and a hardener. The compound prevents leakage through joints of sidewalls and the base of the still [22].

Since solar radiation has three components for the receiving surface namely, absorption, reflection, or transmission.

To account for these characteristics, we introduce additional properties:

- Absorptivity, α , as the fraction of incident radiation absorbed.
- Reflectivity, ρ , the fraction of incident radiation reflected.
- Transmissivity, τ , the fraction of incident radiation transmitted.

We see, from conservation of energy:

$$\alpha + \rho + \tau = 1 \quad (3)$$

Since the solar still includes opaque surfaces, as we are painted the walls with black,

$$\tau = 0, \text{ so that: } \alpha + \rho = 1$$

The basin of the still was also painted black. Owing the height (h) of 0.2 m and area (A) of 0.9 m² basin has the capacity of

$$V = h \times A \quad (4)$$

$$0.900 \times 0.2 = 0.180 \text{ m}^3 \text{ or } 180 \text{ L}$$

Through the sidewalls, the distillate was collected via streamline channels. In an enclosed basin tank that was subjected to the solar radiation was filled with tap water via the inlet valve. Temperatures of water, glass cover, and water-vapor mixture were noted every hour using thermocouples of k-type, which have an accuracy of $\pm 0.2^\circ\text{C}$ and a least count of 0.1°C [23–25].

Distillate collected was also measured during temperature recording. Solar intensity falling on solar still was taken from the reading measured by Pyranometer. We had statistical knowledge from SynergyEnvio-Engineerings that around Udupi, Karnataka (*Latitude: 13.35, Longitude: 74.75*). Annual average of solar irradiation (E) is 5.44 kWh/m²/day.

*With an area of 0.9m² translates to $A * E = 5.44 * 0.9 = 4.895 \text{ kWh/day}$ on a bright sunny day.*

For approximately 90 bright sunny days in summer, this translates to (90×4.895) or 440.55 kWh.

440.55 kWh energy per still, considering a rooftop has room for 10 stills (maximum space needed is 13 m²), this energy is equivalent to 4405.5 kWh [18].

2.2.2 Solar distillation without PCM

Water was the sole element in the still influencing the heat released and the rate of interphase mass transfer. So we studied the water up to two depths 0.05 and 0.07 m and calculated relevant parameters [20].

2.2.3 Experimental investigation to find the effect of PCM on solar distillation

The PCM material was evenly distributed and covered by a 5-mm thick metal plate. The sides of the metal plate were sealed using M-Seal chemical to avoid leakage or contact of PCM and water. The same solar distillation experiments were conducted with a fixed amount of different PCM, and the distillate collected was

recorded on an hourly basis; 5 kg of phenol as PCM was used to perform the experiments at 0.05 and 0.07 m.

3. Results

We have used single-basin, double-slope solar distillation still for the study and hence the results have signified the need for multi-slope and multi-basin for improved performance. Observations were made for water temperature (T_w), top condensing surface temperature (T_g), and distillate output in mL. The temperature of water and glass was measured using two k-type thermocouples. The vapor temperature (T_v) was taken as the average water temperature and glass temperature.

$$T_v = (T_w + T_g)/2 \tag{5}$$

3.1 Solar distillation readings at various heights

Tables 1 and **2** describes the variation of water temperature recorded from 8:30 am until 5:30 pm in 9 hours, each with different heights of water—5 and 7 cm respectively. Water and condensing surface temperature are averaged and recorded in a separate column, which is correlated with distillate collected, **Figures 6** and **7** show variation of temperatures T_w , T_g , and T_v with increasing time in hours. As the day progresses till noon, the water temperature increases faster as compared to the condensate temperature due to exposure of the glass surface to the ambient atmosphere. Alteration in condensate and water temperature can be attributed to unstable climatic conditions. However, in all cases, the pattern followed by the hourly variation shows a constant rise and fall in all line plots (**Figure 8**).

It can be inferred from the above implications and **Figures 7** and **9** that the yield of distillate and the pattern of rising and falling of the curve is similar indicating no variation upon water depth change. The temperature of the condensing surface temperature is rising since morning till past noon and decreases after maxima. We can notice that the temperature variation of water basin coupled with PCM, as shown in **Figures 10** and **11** show similar and broader variation when compared to the curves of water in **Figure 8** and **9** [26, 27]. In the early hours of the day, the

S.No.	Time (h)	T_w (°C)	T_g (°C)	T_v (°C)	Distillate (mL)
1	9	30.3	28.3	30.01	0
2	10	39.3	32.7	36.3	23
3	11	45.6	37.2	421.4	106
4	12	52.2	44.1	47.15	204
5	13	54.3	52.7	52.5	287
6	14	56.1	53.3	55.7	348
7	15	55.2	48.3	53.55	273
8	16	49.1	45.7	48.2	217
9	17	48.7	38.5	42.65	149

Water depth = 0.05 m.

Table 1.
Experimental results without PCM.

S. No.	Time (h)	T _w (°C)	T _g (°C)	T _v (°C)	Distillate (mL)
1	9	30	27.8	29.95	0
2	10	35.3	32.8	36	5
3	11	41.2	37.6	41.4	9
4	12	48.7	43.8	48.15	109
5	13	51.3	47.4	53.5	201
6	14	54.8	50.8	54.7	330
7	15	52.3	45.3	52.55	292
8	16	48.7	39.1	47.2	215
9	17	45	34.2	41.65	157

Water depth (d) = 0.07 m.

Table 2.
Experimental results without PCM.

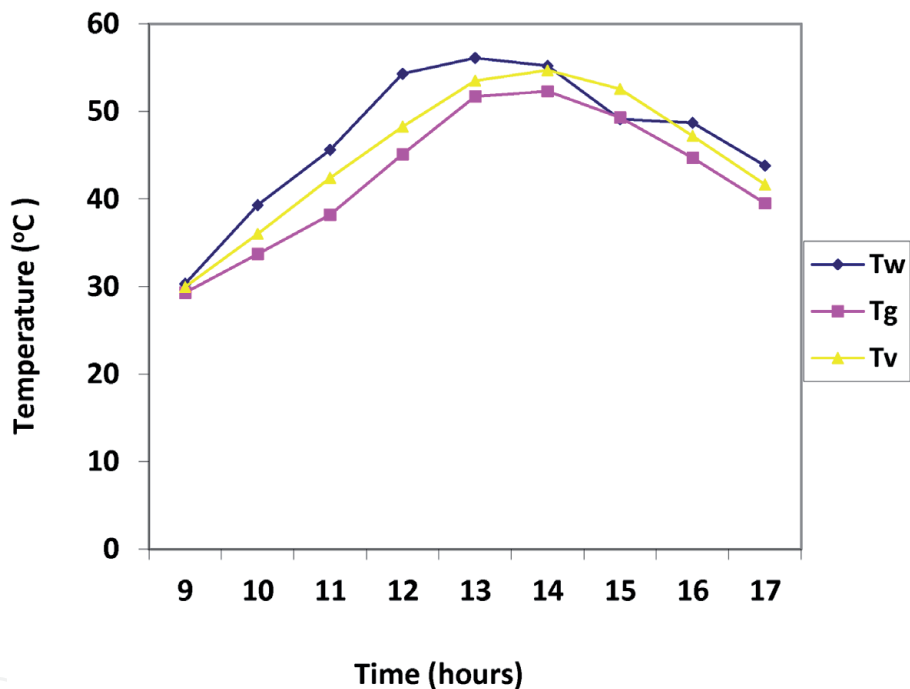


Figure 6.
Hourly variation of temperature at water depth-1.

inner glass temperature is close to that of water basin temperature. However, as the day progresses the difference broadens because water can absorb some of the incident solar energy, whereas glass transmits most of the incident solar intensity. From figures about PCM phenol, we can see how phenol is retaining the solar energy, which decreases the slope of the line, which indicates declining temperature with an increase in hours.

3.2 Solar distillation using PCM

Five kilograms of phenol was covering the 5-mm metal plate in the solar still basin while the experiment was being conducted, there was no mixing of water and PCM. The reading of these experiments was taken on an hourly basis till 5.00 pm and the cumulative distillate of the next 2 h was taken the next day at 9.00 am [8].

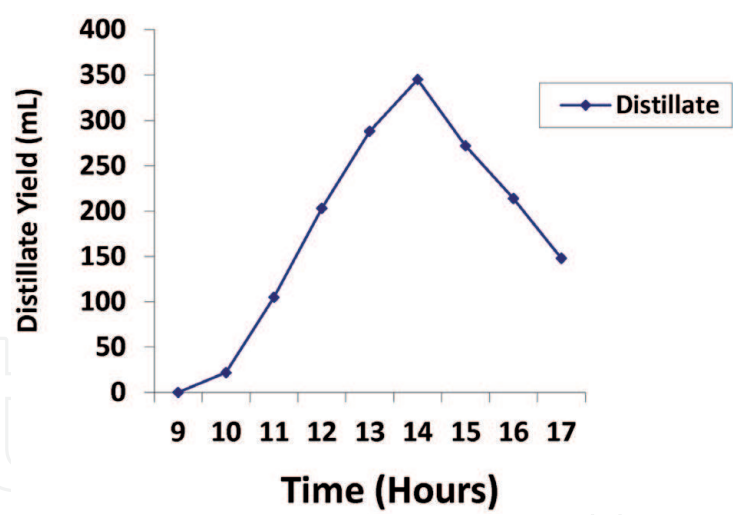


Figure 7.
Hourly variation of distillate yield at water depth-1.

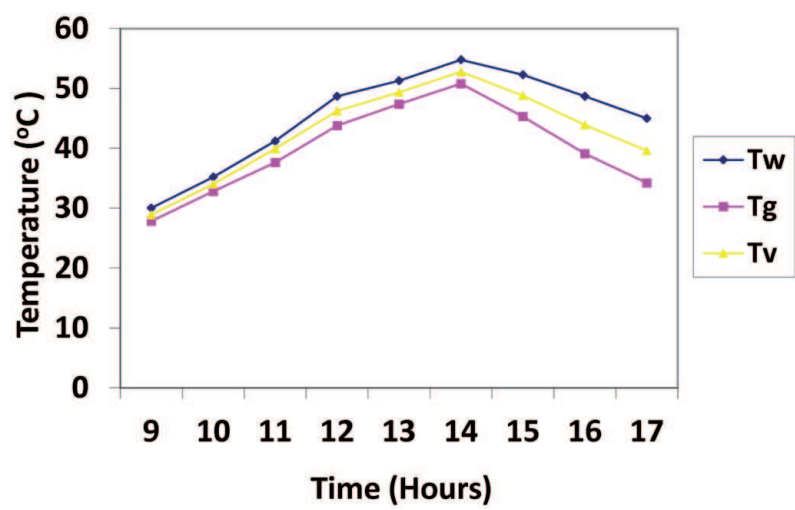


Figure 8.
Temperature variation at water depth-2.

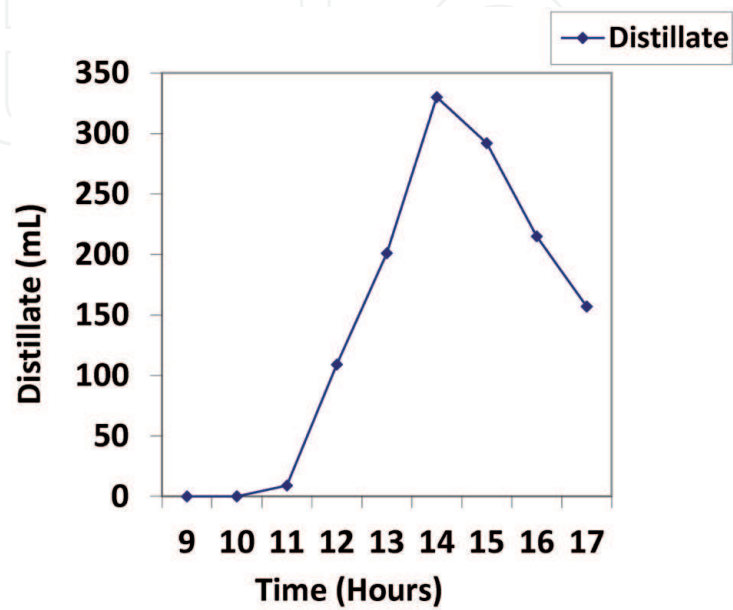


Figure 9.
Hourly variation of distillate yield at water depth-2.

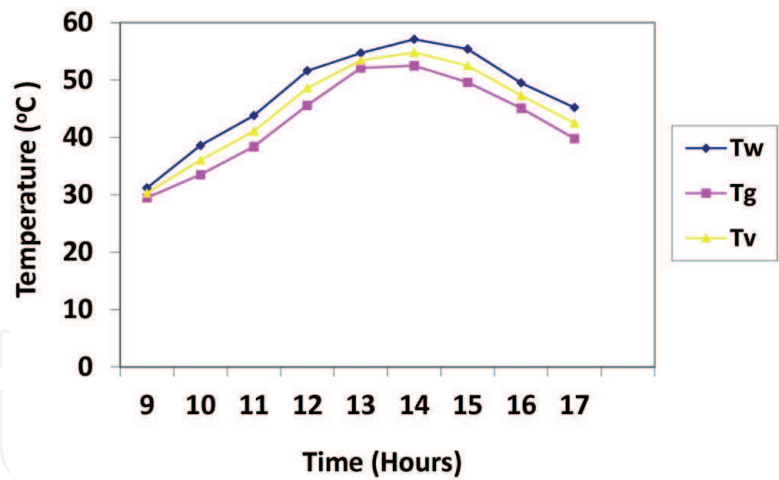


Figure 10.
Hourly variation of distillate with phenol as PCM-1.

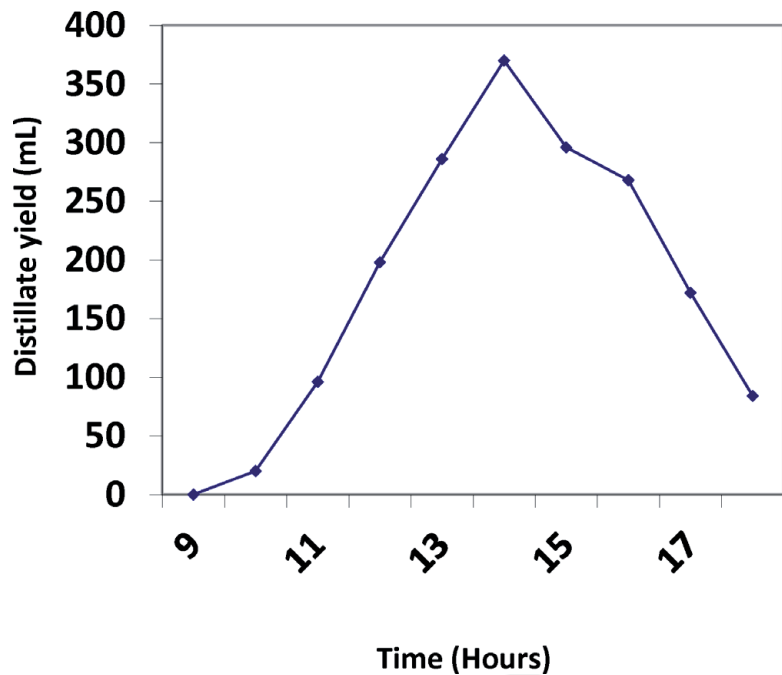


Figure 11.
Hourly variation of distillate yield with phenol as PCM-2.

3.2.1 Solar distillation with phenol as PCM

In **Figures 12 and 13**, it can be seen that the highest temperature attained by the water basin decreases with an increase in depth of water as in the case of PCM with and without PCM too (**Tables 1 and 2**). However, the standard deviation when Phenol as PCM is comparatively larger (**Tables 3 and 4**). In **Figures 10 and 11**, it can also be observed that for phenol, there has been a 4.1% drop in the maximum condensate surface temperature when the water depth has been increased from 5 cm to 7 cm. The decrease in water basin temperature with an increase in depth of water can be attributed to an increase in the volume of water. After sunset, due to a lack of solar radiation, the temperature of water in the basin decreases at a slower rate due to the use of stored heat energy from the PCM. The variation between water basin temperatures in two cases without phenol and with phenol at different water depths is subject to environmental conditions like fluctuation in solar radiation, wind speed, ambient temperature, and spatial wind barriers.

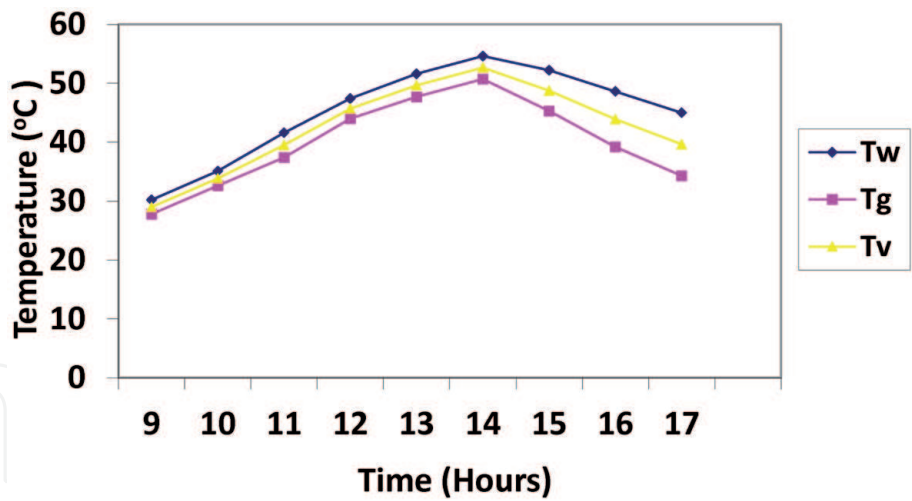


Figure 12.
Hourly variation of temperature with phenol-1.

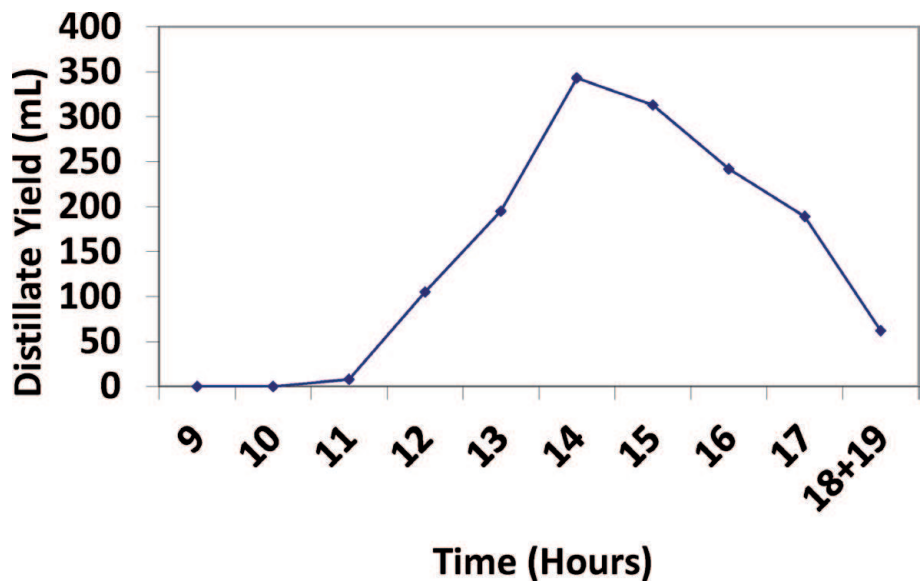


Figure 13.
Hourly variation of temperature with phenol-2.

S. No.	Time (h)	T _w (°C)	T _g (°C)	T _v (°C)	Distillate (mL)
1	9	31.8	29.5	30.35	0
2	10	38.6	33.5	36.05	28
3	11	43.8	38.4	41.1	95
4	12	51.6	45.6	48.6	193
5	13	54.7	52.1	53.4	286
6	14	57.1	52.5	54.8	370
7	15	55.4	49.6	52.5	297
8	16	49.5	45.1	47.3	268
9	17	45.2	39.8	42.5	1760
10	18 + 19	—	—	—	84

Water depth = 0.05 m.

Table 3.
Experimental results with phenol as PCM.

S. No.	Time (h)	T _w (°C)	T _g (°C)	T _v (°C)	Distillate (mL)
1	9	30.2	27.8	29	0
2	10	35.1	32.6	33.85	5
3	11	42.8	37.4	39.5	8
4	12	47.4	44	45.7	115
5	13	51.6	47.7	49.65	195
6	14	54.6	50.7	56.78	323
7	15	52.2	45.3	48.75	313
8	16	48.6	39.2	43.9	242
9	17	45	34.3	39.65	189

Water depth = 0.07 m.

Table 4.
Experimental results with phenol as PCM-2.

4. Discussion

The rationale behind conducting this study was to establish a clear relationship between incident solar radiation and the amount of fresh water produced. After developing the relationship and analyzing statistical information, we concur with the results from confirming data with two different depths [28, 29]. Then PCM was introduced, we chose phenol having attributions of economic availability and versatile properties. Phenol was also varied between two heights, and data was contrasted with that of water. Underlying factors were calculated as follows related to the heat and mass transfer [15].

We know from Dunkle [30], the hourly evaporation per m² from solar still is given by:

$$Q_{ew} = 0.016h_{cw}(P_w - P_g) \tag{6}$$

where,

$$Nu = h_{cw}d/k = C (Gr Pr)^n \tag{7}$$

*C and n are constants.
Also, the heat produced or*

$$Q_{produced} = m_w * L = UA\delta T \dots \delta T = T_a - T_b, \tag{8}$$

which is approximately (T_a – T_w) as basin and water temperature is almost the same, basin being assumed a black body.

Above gives a model to find Q and A for the required basin the fraction Q/A yields the power in kWh/m².

4.1 Effect of the amount of water

For a fixed amount of water, the cumulative amount of freshwater produced had a steep rise as the sun goes higher until sunsets (**Table 5**). PCM, however, continue to heat the water even after the sunset giving the effect of evaporation a boost. We are assuming this as a unit operation under steady-state conditions because we are assuming that the feed water equals the sum of the rate of freshwater produced

S. No.	Height (m)	PCM	Distillate collected (mL)
1	0.05	No PCM	1595
2	0.05	Phenol	1788
3	0.07	No PCM	1333
4	0.07	Phenol	1478

Table 5.
Cumulative distillate collected results.

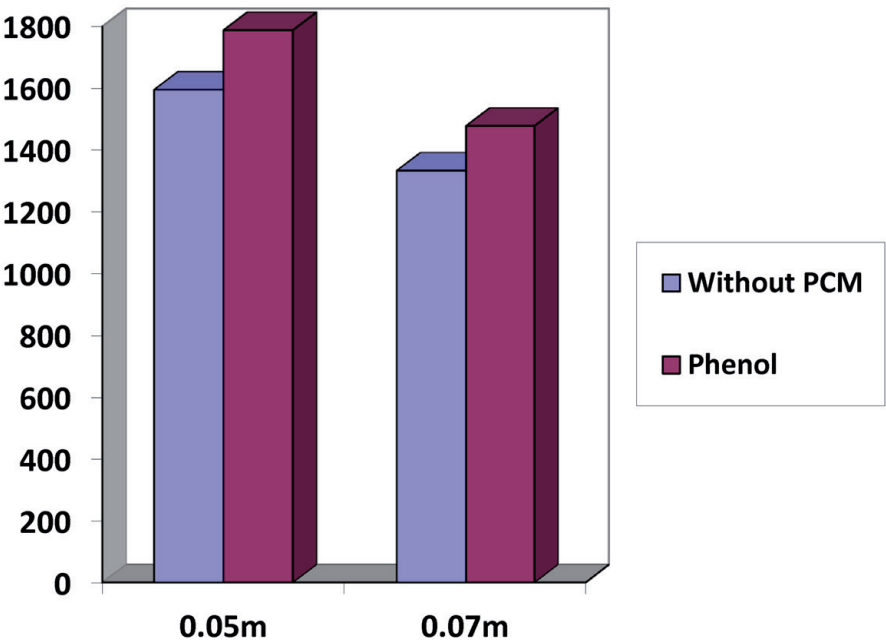


Figure 14.
Cumulative distillate collected at two heights.

and the rate of hot water leaving the unit. Accordingly, the productivity of the unit decreases since the vapor pressure decreases. One also can notice (Figure 11) that the rate of production is significant during the day time and gets lower after sunset. The outcome of variation of height is that the amount of distillate collected reduced with the increase in the height of water in the solar still (Figure 14) [31, 32].

4.2 Advantage of solar still with PCM over ordinary solar still

The potential advantages of solar still with PCM (phenol) are numerous, including flexibility, processability, low material cost, and independence on scarce resources. The flexibility as an advantage is shared with solar cells and solar energy storage panels and is a feature allowing the solar stills with PCM to be incorporated into applications where flexibility is an advantage. Such solar stills that can be rolled out onto a roof or other surfaces are one option. Processability is another major selling point of PCM infused solar stills. Both solar stills with and without PCM depend on distillation methods wherein sunrays are concentrated by glass requiring massive amounts of energy; with PCM based solar cells, on the other hand, energy is stored and for distillation, which yields distillate of desalinated water and complete setup are have a possibility of implementation on a larger platform. Flexibility and more energy storage capacity allows for up-scaling the production and thus reducing the cost per area of PCM solar stills. The promise of low material cost and minimal use of scarce materials can be realized with optimized PCM solar stills.

5. Conclusion and future scope of work

The rationale behind this research work is to apply and analyze the thermal energy engendered by the PCM using the incident solar radiation. The practical work conducted at two water depths concludes the inverse proportionality between the water level and heat released by water; we relate this to the volume occupied by the water in the still. It also follows that, as the water depth decreases, the distance between the top condensing cover and surface of the water also increases, affecting the distillate production.

- The cumulative distillate yield at 0.05 m in the double-slope solar still was 1595 mL, and 1788 mL when the experimented with no PCM, phenol as PCM.
- The cumulative distillate yield at 0.07 m in the double-slope solar still was 1333 mL, and 1478 mL, when the experimented with no PCM and phenol as PCM,
- The effectiveness of PCM to be used to enhance solar distillation intersected with the depth of water in solar still as the efficiency of still changed.
- Phenol gave an increase of distillate yield of nearly ~11.5%.

The data available could be used to prepare the theoretical model to predict the performance of solar stills for solar distillation under the climatic condition in the parts of the world (where the intensity of solar irradiation is around 5.44 kWh/m²/day). Efficient and optimized stills and solar distillation systems are projected as replacing wood with carbon fiber or a more effective insulator. As we can observe in the world map, near the tropic of cancer where solar radiation is potent, and seashore is close, solar distillation is a viable option in case of water shortage. Solar stills are subject to further analysis to separate dirt particles and impurities. Stills can also be used in groundwater as well as tap water to improve the quality of water by removing dirt and unwanted particles. In essence, solar distillation would play a vital role in meeting world freshwater supply demands. The data obtained could be used to investigate the scope of solar distillation further. From this investigation, we discovered that for domestic application, double-basin single-slope cascade solar still is a suitable and economical design.

Nomenclature

C	constant
b	average spacing between water and glass surface (m)
d	the depth of the water (m)
Gr	Grashoff number (dimensionless)
A	area of the basin (m ²)
h_{cw}	convective heat transfer coefficient from water surface to glass (W/m ² °C)
k	thermal conductivity (W/m °C)
L	latent heat of vaporization (J/kg)
m_w	yield of still per unit area per hour (kg/m ² /h)
P_g	partial vapor pressure at glass temperature (N/m ²)
E	energy of incident radiation
P_w	partial vapor pressure at water temperature (N/m ²)
T_a	ambient air temperature (°C)
T_b	basin temperature (°C)

T_g	average glass temperature ($^{\circ}\text{C}$)
T_w	average water temperature ($^{\circ}\text{C}$)
T_{w0}	temperature of basin water ($^{\circ}\text{C}$)
U_L	overall heat transfer coefficient ($\text{W/m}^2\text{ }^{\circ}\text{C}$)

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