Progresses in Solar Still Technology with Phase Change Material

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Abstract. The demand of fresh water is continuously increasing due to frequent rainfalls, shortage of ground water and pollution of natural resources via industrialization. Therefore, solar desalination of available saline and brackish water using solar still is gaining importance among the scientific community for domestic, irrigation and drinking purposes owing to be an economical and sustainable approach of producing fresh water with a simple working principle. Currently, continuous efforts have been made to improve the productivity of solar still by various techniques and configurations. A critical review of solar stills with phase change material (PCM) is presented. This paper highlights the impacts of design specifications along with an economic analysis and the type of PCM material used in recent past. Furthermore, a detailed discussion has been provided on future scope with recommendations to improve the productivity of fresh water for sustainability.

1. Introduction

Fresh water is an essential sustenance of humankind and its demand is increasing constantly due to industrialization, transportation, population growth, and agriculture. Only 2.5% of the total available global water is the fresh water and about 0.3% is in liquid form for living things (Figure 1). However, its distribution on the earth surface is not uniform. Arid and semiarid countries have serious periodic droughts, while there is significant shortage of potable water in deserts and islands; therefore, it is essential to look for alternatives to convert saline water into fresh water [39-40]. The purification of salty/brine water is not possible automatically, but it requires a desalination system. Generally, the desalination schemes are categorized into two groups depending on the working principle of salt separation. First scheme is evaporative/thermal purification, where the clean water is gained by means of evaporation and condensation phenomenon (i.e. phase change of water). The other category is membrane desalination approaches, where fresh water is obtained using pressure driven selective membrane processes (i.e. without phase change of water) [1, 2].

Among all alternatives, solar desalination appears as one of the most economical and viable method of brackish water purification due to usage of solar energy for evaporation of water which is available freely in abundance [3]. The solar still is a very simple and most promising technology to produce bulk amount of fresh water from saline water and found to be suitable in satisfying the demand of fresh water in small communities, especially in remote areas. Evidently, the productivity of conventional solar still is generally low [4, 5], thus, substantial efforts have been made by the researchers worldwide to improve the productivity of solar still by modifying its design, coupling with flat plate/parabolic collector, using heat storage materials [6-8].
Recently, the use of phase change material (PCM) for accumulation of latent heat is emerged as one of the most promising methods to boost the yielding of freshwater of solar stills [8]. Thus, the present article provides a comprehensive review of the ability of PCMs to increase the output of active/passive solar stills considering their different designs and configurations.

2. Working mechanism of Solar still

Figure 2 presents the basic structure of a typical conventional solar still [7, 9]. The readers can refer to the review article written by Kalita et al. [7] to know the details of solar still and its components. The working of a solar still is governed by evaporation and condensation heat transfer mechanisms. Firstly, the basin made up of copper/aluminium/galvanized iron (GI) sheet is filled by the saline water to a particular level and kept under the sun. The incident solar energy is transmitted to the water through the glass and absorbed by the black absorber plate. Once water starts heating and absorbs enough amount of energy, then water vapor escapes at the interface of liquid surface. The generated vapor travel to the condenser section and condensed due to temperature difference at the glass surface. The condensate mass slides over the inclined glass and can be collected in a measuring jar. The purification takes place inside the solar still through phase change heat transfer. Consequently, condensate obtained is suitable for household needs, whereas the contaminations are settled at the bottom of the still [10].
3. Solar Still with PCMs
In open literature, it has been reported that, several parameters such as location, solar irradiance, ambient temperature, wind velocity, water depth, glass cover material, thickness, insulation, inclination, and heat capacity significantly affect the yielding of fresh water [6, 7, 11]. Apart from modifying the shape of solar still (single/double slope, single/multi basin, square and triangular pyramid, semi-spherical and spherical, and tubular-type), the researchers have examined other modifications such as cooling of glass cover, fins, thermal energy storage (sensible/latent), nanoparticles, coupling with flat and concentrating type collectors, flash evaporator, and solar ponds [1, 7, 11-17]. However, this section presents the review of current studies, from 2016 onwards, conducted with use PCMs to enhance the output of solar still.
Sundaram and Senthil [18] investigated the effect of PCM inside a double slope solar still, as presented in Figure 3, having East-West orientation at different water depths (10, 20 and 30 mm). Experimental results disclosed that the distillate is increased by 11.6% with PCM at a water depth of 10 cm, and distillate decreases with further increase in water depth.
Kuhe and Edeoja [19] coupled a parabolic concentrator with a solar still having PCM (14 kg of beeswax) sandwiched amid the absorber and the bottom of the still (Figure 4). Authors reported about 62% enhancement in fresh water productivity for this modified arrangement.

![Figure 3. Photograph of double slope single basin solar still [18].](image1)

![Figure 4. Parabolic reflector dish coupled single slope basin solar still [19].](image2)

The productivity of solar stills with and without PCM (Paraffin Wax) has been compared by Kabeel and Abdelgaied [20] and found that the distillate yield for solar still is improved by 67.18% with addition of PCM for Tanta city (Egypt). Kabeel et al. [21] further studied a pyramid solar still (PSS) with both v-corrugated absorbers plate and PCM (Figure 5). Interestingly, about 87.4% improvement in distillate yield has been observed for a modified PSS with PCM. From economic analysis, the cost of fresh water output from a still with and without PCM is found to be 0.03 $/L and 0.032 $/L [20], respectively; and for modified PSS with and without PCM is about 0.0236 $/L and 0.0262 $/L [21]. Furthermore, Kabeel et al. [22] tested the effect of inorganic and organic PCMs in single slope still. Their findings showed that the productivity of CSS is increased by 92% with PCM A48, while the lowest cost of 0.0125 $/L is found for capric-palmatic PCM. In another study, Kabeel et al. [23] explored the effect of TiO₂ nanoparticles with black coating on the productivity of a pyramid solar still (Figure 6) at water depth varying between 1 cm to 3.5 cm. Their results revealed that the use of black painted TiO₂ nanoparticles enhanced the water temperature by 1.5°C and increased the water productivity by 6.1% than that of conventional pyramid solar still [41-43].
For the climatic conditions of Tehran (Iran), Faegh and Shafii [24] studied the effect of storing latent heat solar stills using PCMs (Figure 6). The solar desalination facility consists of a tank for storing PCM, evacuated tubes, a saline water basin, a fan and heat pipes. It was reported that the distillate output of novel system is about 86% higher compared to without PCM. Husainy et al. [25] studied the double slope solar still with and without PCM under the actual weather conditions of SIT COE, Yadrav, Maharashtra and reported a 10-25% enhancement in productivity with PCM.
Figure 5. (a) Modified PSS with PCM, and (b) conventional PSS [21].

Experimentally and theoretically, Rufus et al. [26] studied the freshwater productivity improvement for solar stills with PCM and NEPC nanoparticles. Authors observed the daily distillate of about 1.96 kg and 2.64 kg per 0.5 m² respectively for solar still with only PCM and with NEPCM, in other words, about 35% enhancement in fresh water productivity has been observed for solar still with NEPCM than only PCM. Figure 7 shows the double slope solar still with PCM and without PCM along with pebbles, and reflectors fabricated by Naygaonkar and Yadav [27] and found about 45% improvement in yield of solar stills coupled with reflectors and pebbles using PCM as compared to without PCM.

Figure 6. Test carried out for Studied configurations [24].
Shanmugan et al. [28] tested the novel idea of dipping saline water on absorbing materials, namely, cotton wick (CW), jute wick (JW), fin with cotton wick (FWCW), and fin with jute wick (FWJW) inside a single slope solar still with and without PCM (Stearic acid) & nanoparticles (Al₂O₃). The properties Al₂O₃ nanoparticles and PCM material are presented in Table 1. The productivity comparison of solar stills with and without PCM & nanoparticles for a duration of 24 h (day and night) has been presented in Figure 8 and found that the maximum distillate yield reaches up to 9.36 kg/m²/h for Case-4. Performance comparison of various solar stills, i.e. conventional solar still (CSS), solar still with PCM, CSS with PCM embedded in a pin-fin heat-sink, CSS with PCM integrated with steel wool fibres, CSS with only SWF and CSS with pin fined heat sink, has been reported by Yousef and Hassan [29]. The total distillate of still with PCM is about 10% higher than CSS, whilst the still with PCM+SWF is approximately 7% more than CSS+PCM.

To improve the fresh water output of a solar still, Sonker et al. [30] inserted copper cylinder filled with PCMs, as shown in Figure 9. With increase in water depth (1 to 5 cm), the basin temperature decreased by 9.2% for paraffin wax, 17.6% for stearic acid and 21.5% for lauric acid. The fresh water productivity was enhanced by 1202, 1015, and 930 ml/m²-day, respectively, for copper filled with paraffin wax, stearic acid, and lauric acid.
Safaei et al. [31] studied the influence of graphene oxide (GO) (0.2, 0.4 and 0.6 wt.%) in PCM (paraffin wax) on the fresh water productivity of a stepped solar still and reported that increase in concentration of graphene oxide to the PCM significantly reduced the melting temperature. Overall, up to 25% enhancement in fresh water productivity has been observed for solar still with GO/paraffin wax than that of solar still with only PCM.

Khanmohammadi and Khanmohammadi [32] analysed the economic, exergy efficiency, and environment impact of a cascade solar still (Figure 10) integrated with various insulations and PCMs, as reported in Table 2. It has been found that among various configurations phenolic foam produces the maximum amount of freshwater, about 9.42 kg/m²/day. While, the desalination system coupled with paraffin as PCM and glass wool as insulation, showed the lowest total annual cost, about 71.67 S. Kabeel et al. [33] experimentally investigated the effect of coupling an internal reflector and composite black gravel-PCM (Figure 11), as thermal heat storage on the fresh water productivity, energy, exergy, and economic aspects of solar still under the environmental conditions of Birkat Elsab City, Monufia, Egypt. The authors reported that the solar still with composite black gravel-PCM provide about 37.55%, 38% and 37% improvement in distillate output, energy and exergy efficiency, respectively, than the solar still with PCM only. While, the cost of fresh water production for composite material is about 27% lower than only PCM.

**Figure 9.** (a) Passive solar still with PCM and (b) PCM loaded copper cylinders [30].

**Figure 10.** (a) Cascade weir type inclined solar still, and (b) an enlarge view of steps and weirs. [32].
Table 2: Properties of PCMs employed [32].

| PCM                  | Thermal conductivity (W/m K) | Specific heat capacity (J/g K) | Melting temperature (°C) | Latent heat (J/kg) |
|----------------------|------------------------------|--------------------------------|--------------------------|--------------------|
| Paraffin             | 0.240                        | 2950                           | 56                       | 226000             |
| nePCM I (Paraffin + TiO$_2$) | 0.325                       | 2940                           | 58.5                     | 118000             |
| nePCM II (Paraffin + CuO)  | 0.335                        | 2850                           | 59                       | 168000             |
| nePCM III (Paraffin + GO)  | 0.523                        | 2870                           | 57.5                     | 64700              |
| Stearic acid         | 0.290                        | 1590                           | 52                       | 169000             |

Through experimental and simulation, Cheng et al. [34] assessed the effectiveness of a PSS with a new shape-stabilised paraffin wax, as a PCM (SSPCM). Their findings showed that the daily productivity of solar still with SSSPCM is about 43.3% more than CSS without SSSPCM. While, simulation results revealed that the fresh water productivity for SSSPCM is increased from 42% to 53% and 21.5% to 57.5%, with increase in thermal conductivity of SSSPCM from 0.2 to 4.0 W/mK and melting temperature from 34 °C to 50 °C, respectively, as compared to CSS.

Modi et al [35] studied the effect of nanoparticles on the fresh water productivity of a dual-slope solar still at different glass cover orientations and water depth in basin. For North–South orientation, the daily of distillate yield was enhanced by 19.40%, 28.53% and 26.59% with Al$_2$O$_3$ nanoparticles at water depths of 30, 20 and 10 mm, respectively; while improvement of about 58.25% and 56.31% was witnessed with CuO nanoparticles at water depths of 20 and 10 mm, respectively.

**Figure 11.** Solar still with composite material bed [33].
Kabeel and Abdelgaied [36] introduces a novel idea of cooling glass cover along with a high thermal conductivity absorber plate (graphite, thickness of 25 mm) for improving the performance of PSS. Authors reported the enhancement of freshwater output ranges from 105.9 to 107.7% for modified pyramid-shaped still than that of traditional solar still for the climatic conditions of Tanta University-Egypt. Use of graphite absorber plate and cooling glass cover inside the pyramid-shaped still increased the daily efficiency by 97.2–98.9% and reduced the cost of freshwater production by 13.6% when compared with CSS. Recently, Kabeel et al. [37] investigated the effect of introducing nanomaterial (graphene oxide) in PCM inside a tubular solar still on the productivity for the environmental conditions of Chennai, India (Figure 12). Their experimental findings revealed that with application of NPCM, the evaporation rate of tubular solar still is increased by 41.3%, and the daily efficiency is enhanced to 116.5%. Singh P. K. et al. [38]

![Diagram](image)

**Figure 12.** Schematic of (a) TSS, (b) TSS with PCM and (c) TSS with NPCM [37].

4. Summary and Future Prospects

Based on above discussed literature review, it is clear that the research community has paid significant attention towards improving the performance of solar stills. In the present paper, the authors reviewed the studies available in pertinent literature, mainly focused on productivity enhancement of solar still using phase change materials in recent years, and a brief summary is presented in Table 3. From Table 5, the researcher can clearly see that with integration of PCM in the solar still significantly improve the fresh water productivity of the still and also leads to remarkable drop in the total annual cost of distillate yield. Still further investigations are required on the current design of solar still in order to augment the fresh water output, and subsequent research ideas may be employed and recommended as a future scope of research for achieving improved performance of passive solar stills.

- To improve the productivity of inclined solar still, proper glass cover orientation/tracking adjustments are needed so as to capture maximum amount of solar radiation and reduced shading effect. While, no such tracking adjustments are required in case of square pyramid type solar still.
- To acquire maximum solar radiation, concentrators/reflectors (flat/parabolic/spherical/mirrors) can be coupled with the solar stills for increasing the output efficiency.
- The use of wick materials along with PCM with a glass cover cooling arrangement should be tested as modifications of the existing design of passive solar stills.
- Fins with different shapes could be used to increase the water evaporation rate and thereby the better fresh water productivity, however, the distillate output can further be increased if the fins are filled with composites of PCM and nanoparticles.
- Further studies are required to see the effect of adding PCM and heat pipes in the basin of solar still in a cost effective manner.
Some of the recent investigations also recommended the need of further investigations in the field of nano-technology with the intention of integrating nanomaterials with PCM inside the basin for increasing the productivity even during the off-sunshine hours.

Conclusively, from future prospective, the researcher can try integration of external components (reflectors/concentrators/fans), hybridization of active/passive schemes, use of different materials with PCM in modified designs of solar stills and practical approaches should be used effectively and efficiently in order to augment the performance of solar desalination technology.

### Table 3: Studied solar stills with phase change materials.

| Authors                  | Design of Solar Still | PCMs                                      | Productivity                                      |
|--------------------------|-----------------------|-------------------------------------------|---------------------------------------------------|
| Sundaram and Senthil [18]| Double slope          | Paraffin Wax                              | Yield increases by 11.6% with PCM at a water depth of 10 mm |
| Kuhe and Edeoja [19]     | Single slope solar still with parabolic reflector dish | Bees wax                                   | • Concentrator coupled with CSS = 3240 ml/m²/day   |
|                          |                       |                                           | • Concentrator coupled with CSS + PCM = 5243 ml/m²/day |
| Kabeel and Abdelgaied [20]| Single slope          | Paraffin wax                              | CSS = 5.41L/m²                                    |
|                          |                       |                                           | CSS + PCM = 7.54 L/m²                              |
| Kabeel et al. [22]       | Single slope          | Inorganic and organic PCMs                | Maximum productivity = 6.6 kg/m² for PCM A48       |
| Kabeel et al. [23]       | Pyramid               | TiO₂ nanoparticles                        | Maximum yield = 6.6 kg/m²                           |
| Faegh and Shaffi [24]    | Single slope solar still with evacuated tubes | Paraffin wax                              | Productivity increases by 86% with PCM             |
| Husainy et al. [25]      | Double slope          | Paraffin wax                              | Productivity of solar still increases by 25% with PCM |
| Rufuss et al. [26]       | Single slope          | Paraffin wax and CuO nanoparticles        | CSS + PCM = 3.92 kg/m²                             |
|                          |                       |                                           | CSS + PCM + CuO nanoparticles = 5.28 kg/m²         |
| Naygaardoankar and Yadav [27]| Double slope single basin solar still with reflectors | Paraffin Wax                              | CSS + Reflectors = 1.45 L/m²                       |
|                          |                       |                                           | CSS + Reflectors + PCM = 2.01 L/m²                 |
| Yousef and Hassan [29]   | Inclined              | Paraffin Wax, Fins (PF), Steel Wool Sheet (SWF) | CSS = 3.262 kg/m²                                 |
|                          |                       |                                           | CSS + PCM = 3.572 kg/m²                            |
|                          |                       |                                           | CSS + PCM + Fins = 3.8094 kg/m²                    |
|                          |                       |                                           | CSS + PCM + SWF = 3.685 kg/m²                      |
|                          |                       |                                           | CSS + SWF = 4.08 kg/m²                             |
|                          |                       |                                           | CSS + PF = 3.78 kg/m²                              |
| Reza et al. [31]         | Step slope            | Graphene Oxide/Paraffin                   | 1.0 kg/m²                                         |
| Kabeel et al. [37]       | Tubular               | Paraffin wax, Paraffin wax + graphene oxide | TSS = 2.59 kg/m²                                  |
|                          |                       |                                           | TSS + PCM = 3.35 kg/m²                             |
|                          |                       |                                           | TSS + NPCM = 5.62 kg/m²                            |

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