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Improving the solar still performance by using thermal energy storage materials: A review of recent developments

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ABSTRACT

In recent decades, energy and water desalination using solar energy has played a vital role for the survival of human beings due to the cost and shortage of clean water; and gave considerable impetus to decrease greenhouse gas effects produced from burning fossil fuels. Thermal energy storage materials (TESMs) are used to store the energy through the daytime (sunshine time) and discharge this energy during nighttime (sunset time) and hence they have been used in water desalination systems to enhance its performance. TESM such as phase change materials (PCMs), myristic acid, sponge's cubes, cotton, jute, cloth, porous materials and sponge sheet, quartzite and natural rock, coated and uncoated metallic wiry sponges, sand, gravels and aluminum filling are quite attractive in the solar desalination, especially in solar stills (SSs), to enhance thermal performance of SS by improving its thermal energy storage capability. We found from this review that the TESMs have a significant effect on enhancing the fresh water output from the SS especially when paraffin wax is used as PCM, which has large storage density with narrow range of temperature difference. In this review paper, various solar TESMs, especially PCM, tested by the researchers to improve the freshwater output as well as thermal performance of SSs, are analyzed and discussed in detail.

Keywords: Solar still (SS); Thermal energy storage materials (TESMs); Phase change materials (PCMs); Freshwater output; Review

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1. Introduction

Freshwater is necessary for life and its shortage is increasing all over the world day by day, especially in arid areas such as deserts, industrial regions and so on. The complicated issue occurs in distant zones and islands where potable water feeding over any transportation wherewithal is costly. It is well known that approximately 99% of available water in the earth is salty or brackish, and only 1% is fresh. Despite of the abundance of seawater, the salinity removal processes require additional expense of energy. Enhancing the effectiveness and efficiency of water cleaning technologies to get fresh water and minimize the environmental impact in a prospective way is reasoned as the major defy of the 21st century [1]. Then, earnest efforts are underway all over the world to avert this problem with keeping of the existing restricted potable water feeding and to alter the major quantities of obtainable non-potable water by various desalination technologies such as thermal technologies comprise vapor compression (VC) [2], multi stage flash (MSF) [3], multi effect distillation (MED) [4,5], humidification-dehumidification (HDH) [6,7], and membrane technologies like reverse osmosis (RO) [8].

Solar energy as a free abundance energy source has been utilized for the purpose of desalination of impure water (salty or brackish) to produce fresh water [9,10]. However, SS is the best technique used to purify impure or salt water in a small or moderate scale. SSs are usually used in water desalination by solar energy and are very simple in manufacturing, self-operating and required no maintenance [11], but the freshwater productivity of SSs is too low. To improve the productivity as well as the thermal performance of SSs, numerous research studies have been carried out to investigate the effect of different parameters such as metrological parameters, designs and working parameters on SSs' performance. Firstly, the metrological parameters, like solar intensity [12], air temperature [13], wind speed [14] and relative humidity [15], cannot be controlled. Secondly, the design and operational parameters and modifications like insulation thickness [16], glass–water temperature difference [17,18], inlet brine temperature [19], solar still with collectors (active solar still) [20], water depth in the basin [21], tilt angle, material and thickness for glass [22], sun tracking system [23], wood [24,25], wick materials [22,26–28], internal and external condensers [29,30], and internal and external reflectors [31,32], can be applied as control factors to optimize the performance of SSs. Finally, various SSs designs such as stepped SS [33], energy storage materials [34,35], pyramid-shaped SS [36], hemispherical SS [37], tubular SS [38–40], modeling SS using artificial neural network [41], hybrid SS integrated with humidification-dehumidification unit [19,26,42], active single solar still (ASSS), active double slope solar still (ADSSS) integrated with N-thermal photovoltaic (PVT) [43], double slope SS integrated with thermal photovoltaic [44–46], have been proposed to achieve better SS performance under different operating conditions. Recently, with developing nanotechnology, many researchers utilized nanoparticles to improve the evaporation rate and solar still performance [18,44,47–52]. Furthermore, different optimization techniques have been used to select the optimal design and operating parameters of SSs [53]; and energy and exergy analyses have been used to assess the thermal performance of SSs [54].

One of the main drawbacks of solar energy is its discontinuity [55]. To overcome this drawback, energy storage systems are used in many solar energy applications. There are many solar energy applications which integrated with different energy storage systems in our daily life such as air conditioning and refrigeration [56], heat exchangers [57,58], solar cookers [59], cold storage [60], increasing thermal mass using PCM in brick constructive [61], and solar warming and natural cooling (night-time ventilation) [62]. The applications of PCMs in the building construction to obtain thermal comfort by decreasing the heating and cooling request have been reviewed by [63].

Thermal energy storage materials (TESMs) have an increasing concern in many modern technologies. The main idea of TESM applications is to manage the energy level inside the thermal systems by storing thermal energy at periods when it is abundantly available and releasing it when required. Among different TESMs, systems utilizing PCMs are more efficient as they have a reasonable consistent in latent heat storage applications. More research work on the application of PCMs for thermal energy storage and more information regarding its performance are required as a vast range of PCMs are used in solar systems.

Currently, many researchers have investigated the effects of using various types of TESMs on the performance of SSs. However, there is no particular attainable review on SSs with TESMs. In this work, we introduce a documental survey on the use of TESMs in SSs as well as, we aim to review the best appropriate TESMs and PCMs depending on the types of SSs. Furthermore, recommendations for future work have been given.

2. Phase change materials as TESMs

Phase change materials (PCMs) are considered as one of most efficient and commonly used TESMs. The charging process of PCMs, begins in the morning with the sun rise which in turn, increases the water temperature. Also, the heat transferred to the PCMs causes an increase in its temperature gradually through the sensible heat. Finally, the PCMs melt and gain additional heat, without any increase in temperature, called latent heat of fusion. The discharge process occurs at the sun set. The temperature of the water at the base begins to decline and the discharging phase of the PCM occurs through the loss of the latent heat followed by the sensible heat and the transition from the liquid state to the solid-state because of the rejection of the heat to the water in the basin. Therefore, PCMs can be used to store the extra energy during the sunrise periods and release this energy during the sunset periods which may improve the SS productivity.

The performance of the SS is dependent on the solar radiation which has a peak value between 11 am to 2 pm. During this period, the freshwater productivity of the SS reaches its peak value. Furthermore, through this period, the temperature of impure water inside the SS as well as the glass temperature increases due to large amount of solar radiation. The water vapor amount inside the SS will also increase. Furthermore, the distillate water will be increased as it depends mainly on the temperature difference between the water in the basin and the inner surface of the glass cover. That is due to the increase of the natural circulation of the air inside the still and the condensation rate on the inner surface of the glass cover.

In other words, to decrease the temperature difference between the glass and the water in order to improve the condensation rate, TESMs can be used to store the excess energy during sun rise period which is charging period. Then, during sunset, TESMs can be used to increase the water temperature to improve the evaporation as well as the freshwater output which is discharging period. Hence the SS performance is improved by using TESMs. PCMs, especially paraffin wax, were widely used in recent years to store energy in the process of changing the aggregate state from solid to liquid in SS desalination.

2.1. Properties of PCMs

PCMs have a lot of applications such as space heating, water desalination, and water heating. Thermo-physical properties of the TESMs have a great effect on the system performance. Here, the main thermo-physical properties of PCMs will be explained as follows:

- Melting point: PCMs must have a melting point near the operational temperature range of the system.
- Latent heat of fusion: PCMs with high latent heat of fusion have the ability to store more energy.
- Specific heat (Cp): PCMs with high specific heat of fusion have the ability to store more energy.
- Thermal conductivity: PCMs with high thermal conductivity have enhanced heat charging and discharging rates which is required for enhancing thermal performance.
- Density: PCMs should have high energy storage density which results in decreasing the volume.
- Super cooling: super cooling should be lower in PCMs through the freezing process.
- Cost and availability: PCMs should be abundantly available and have cheap price.
- Thermal stability: PCMs should be thermally stable even after large number of heating and cooling cycles.
- Chemical stability: PCMs should be chemically stable.
- Volume change: Volume change of PCMs related to phase change process must be smaller.
- Non-toxic: PCMs should not be harmful to the operators health and the environment.
- Non-corrosive: PCMs must be non-corrosive.
- Flammability: PCMs must be non-explosive and non-flammable.
- Vapor pressure: PCMs must have small vapor pressure in the operating temperature range.

2.2. Solar still with PCMs as a TESM

In recent years the PCMs, as commonly used TESMs, have been widely used in order to store energy during the day (sun's brightness) and take advantage of this stored energy during the night to improve the productivity and the performance of SSs. Naim et al. [64] improved the yield of a SS by using a TESM. The TESM is located in the SS trays. Aluminum turnings were added to a mixture of paraffin oil, paraffin wax and water to improve the heat transfer of the basin water and also to save heat energy through the daytime and lastly release it during the night time. So, the former mixture was used as a special type of PCMs. The productivity was reached a maximum value of 0.851 L/m^{2}h using saline water supply flow rate of 0.40 L/min. Besides, the hourly productivity was increased by more than 0.05 L/m^2 h, when the experiment duration was extended for 2 h after sunset.

El-Sebaii [65] developed theoretical models to improve the SS with and without PCM beneath the basin during summer and winter days. The authors studied the effect of the PCM amount on the daytime, nighttime, and daily productivity, and the efficiency of the SS for different brine depths. The results illustrated that, during the summer day, the productivity of the SS was about 9 L/m^2/d and the efficiency during the daytime was about 85.3% with PCM. However, the productivity was about 5 L/m^2 d when the SS is used without the PCM. The SS with PCM is extra effective for smaller brine water depths on winter days.

Kabeel and Abdelgaied [66] used PCMs (paraffin wax) as a heat storage medium to improve the performance of a SS and increase fresh water yield as illustrated in. Two SSs were designed and manufactured to compare the performance of the still with and without PCMs. The first one is a conventional solar still (CSS) and the second is a modified SS (CSS with PCMs). The experimental data illustrated that, the yield of freshwater for SS with and without PCMs was 7.54 L/m^2 and 4.51 L/m^2, respectively, thus the productivity was enhanced by 67.18% when PCM is used. Furthermore, the cost per one L of freshwater was about 0.24 and 0.252 $ with and without PCMs, respectively

Kabeel et al. [67] practically investigated the effect of using a double passes air solar collector with PCMs on the SS yield as shown in Fig. 1a. Two SS were designed and manufactured to compare the performance of the still with and without PCMs. The first one is CSS and the second one is modified still with PCMs and hot air injection from solar air heater. The results revealed that, the freshwater yield was 9.36 L/m^2/d for the double passes solar air collector integrated with SS, with PCM, while it was 4.5 L/m^2/d for the CSS as illustrated in Fig. 1b, and hence the productivity was increased by 108% by using PCMs and forced hot air bubbles.

Ramasamy and Sivaraman [68] experimentally studied the effects of using PCM (Paraffin wax) on the performance of a stepped SS. A heat tank is combined with a SS and filled by PCMs (Paraffin wax) due to its reliability, safety, and low price. Through the sunshine time, when the temperature of basin plate is larger than the PCMs temperature, the heat will be transport to PCMs and process of the charging will be started to store energy via sensible heat till reaching up the melting point. After melting, more energy will be stored through latent heat. After sunset when the basin plate temperature is smaller than PCMs, the discharging process will start till the PCMs are completely solidified. The results illustrated that the hourly productivity is slightly higher in case of SS without PCM in normal sunny days; the output distillate are 1.68 L /day and 1.85 L/day for 0.76 m^2 area of SS with and without use of PCM, respectively. While the output distillate improves through evening hours the

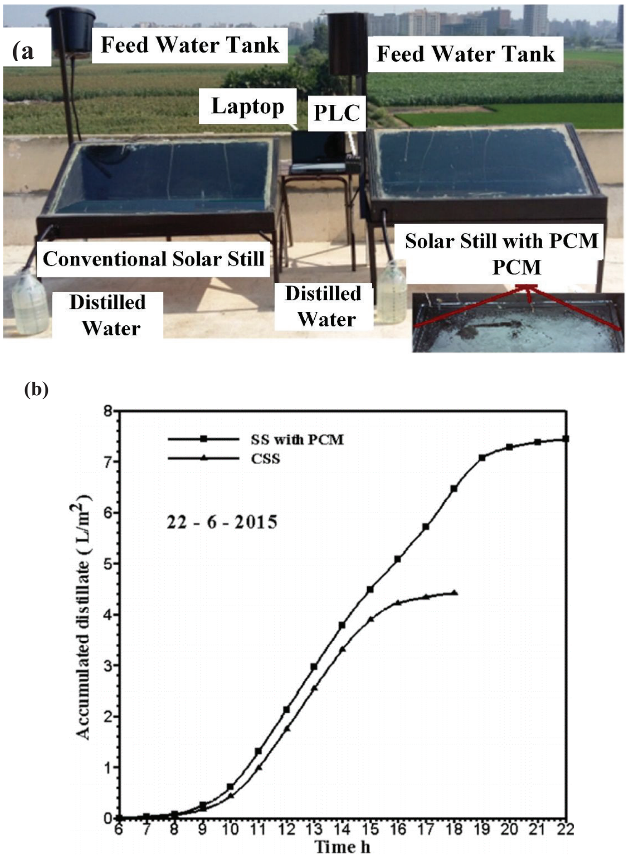

Fig. 1. (a) Photo of the conventional SS and SS with PCMs, (b) the accumulated distillate for conventional and modified SS [66].

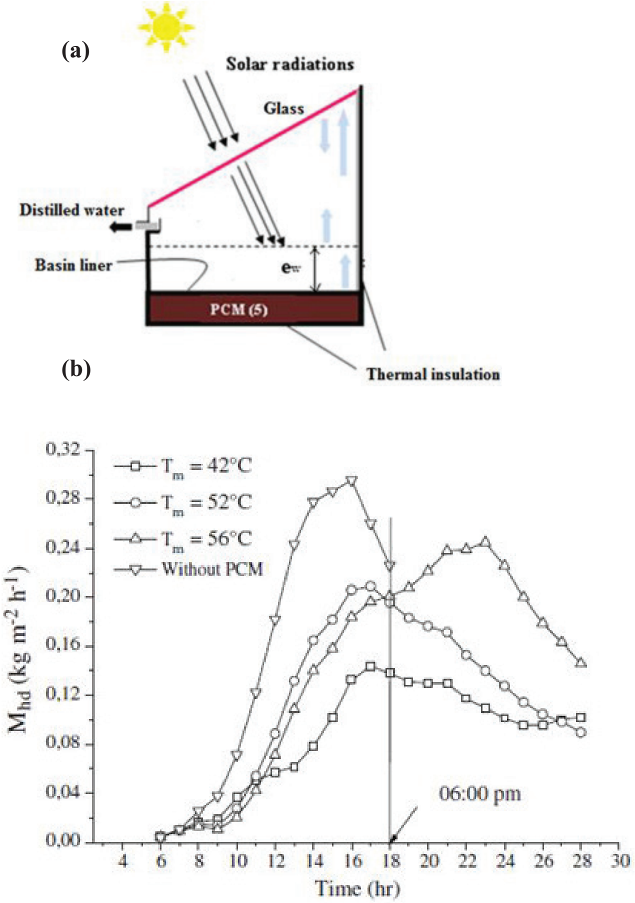

Fig. 2 (a) System schematic diagram, (b) Hourly variations of yield with time (with and without PCM) [69].

productivity of the SS with PCM during nighttime was 0.36 liters but for CSS was zero.

Ansari et al. [69] conducted an experimental and analytical study to investigate the SS performance using PCMs (paraffin wax) under the basin liner of the SS as illustrated in Fig. 2a. The results illustrated that the energy generated through daytime is stocked in PCMs (charging process) to use during the nighttime (discharging process). Fig. 2b illustrates that the differences in the hourly yield produced water for the three different PCMs (paraffin wax with different melting temperature, i.e., Tm = 42°C, Tm = 52°C and Tm = 56°C) compared with CSS. Freshwater output is much larger without PCMs during the daytime compared with the three types of PCMs. Furthermore, after 6:00 pm, SS without PCMs stopped to produce freshwater. On the contrary, the three types of PCMs continue to produce freshwater as illustrated in Fig. 5b. Also, Fig. 5b illustrates that after 6:00 pm, productivity of PCMs with Tm = 56°C increases continuously to reach its highest value at 12:00 am, then decreases to reach the lowest value at 4:00 am. But, for PCMs with Tm = 52°C, freshwater productivity decreases quickly after 6:00 pm. While, freshwater yield slowly decreases in PCMs with Tm = 42°C after 6:00 pm.

Kabeel et al. [70] conducted an experimental study to evaluate the system performance of the SS during summer and winter integrated with PCM (Paraffin wax) and parabolic solar concentrator and compared it with those of CSS as illustrated in Figs. 3a, b. Parabolic concentrator was used to increase and concentrate the total solar irradiance absorbed by the modified SS. Also, the performance of the system was conducted at different brine depth from 1 to 6 cm. The results illustrated that the SS yield with parabolic concentrator and PCM is enhanced by about (55–65%) in summer season and by about (35–45%) in winter season compared with the CSS. The best performance was obtained at lower brine depths as illustrated in Fig. 3c.

Ravishankar et al. [71] conducted an experimental study to augment the distillate water and enhance the efficiency of a triangular pyramid SS integrated with PCM (paraffin wax) applied under the basin. The use of PCM improves the distillate water of the SS by about 20%. Kantesh [72] performed an experimental study to enhance the SS performance as well as the yield of water integrated with PCM (bitumen). The SS productivity and efficiency were improved specially during the sunset hours using PCM. The SS efficiency was about 27% for the SS with PCM, while it was about 25% for CSS. Arunkumar et al. [73] studied the performance of a compound parabolic concentrator-concentric tubular SS (CPC-CTSS). A set of 2 m long concentric tubes with rectangular basins of the same length was fabricated (2 m^2 area) and the entire experimental setup was operated with cold water flow over the inner tubes of the concentric arrangement as illustrated in Fig. 4a. A pale filled with PCM (paraffin wax) - compound with CPC-CTSS has been examined to improve the

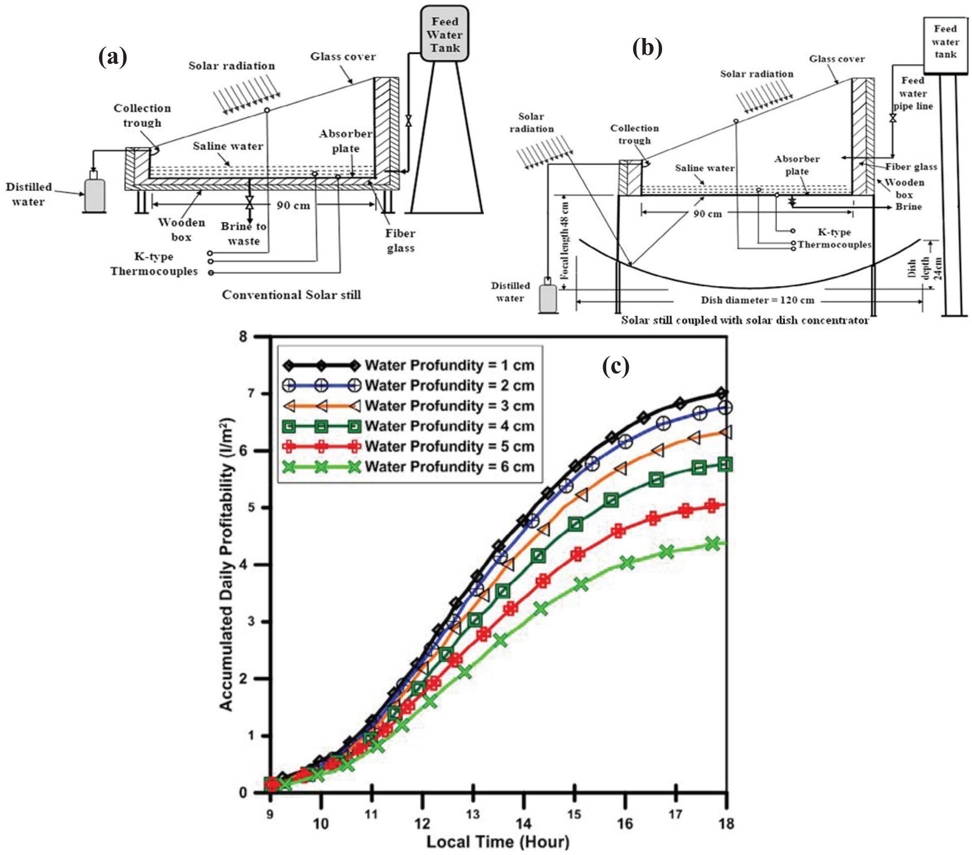

Fig. 3. Schematic diagram of the system: (a) CSS; (b) modified SS with PCM; (c) Average daily accumulated yield for the modified SS at different brine depths [70].

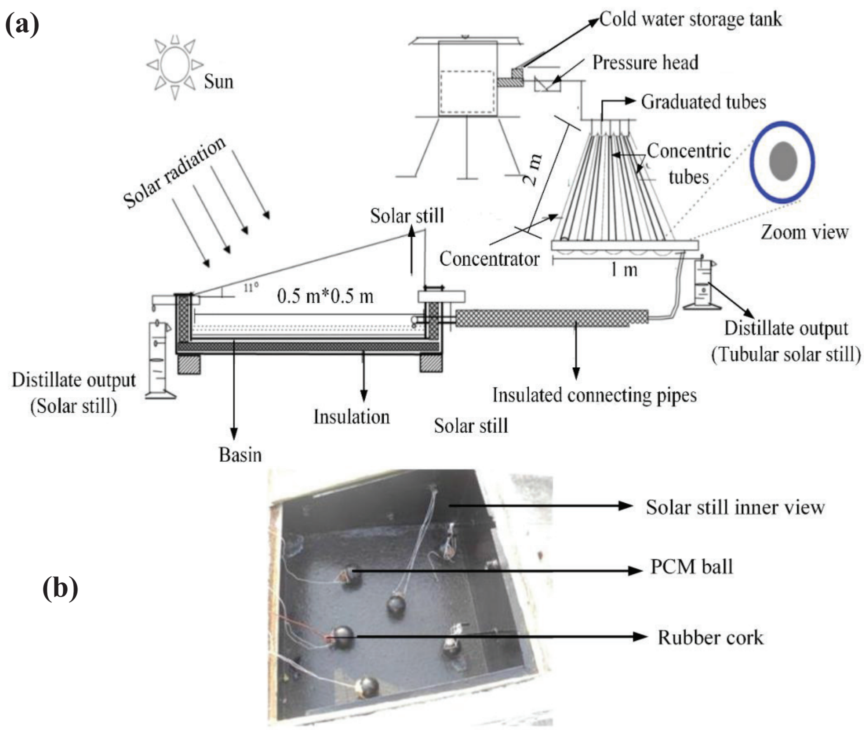

Fig. 4. (a) Schematic view of CPC-CTSS coupled with SS, (b) SS with PCM (inner view) [73].

yield. The basin temperature of the SS was increased due to heat removed from the cooling water of the CPC-CTSS. The beneficial heat extraction plays an important role to improve the yield as illustrated in Fig. 4b. During the nighttime, the PCM works as a heat source to get the evaporation during the nighttime. The results illustrated that the freshwater output from CPC-CTSS was about 3.5 L/m^2/d. With the addition of the SS, the area of collector increased, while the output distillate improved to 2.7 L/m^2/d.

Shalaby et al. [74] proposed a novel design of a v-corrugated basin SS integrated with PCMs. The experiments were carried out with and without the PCM (Paraffin wax) using various brine depths as well as integrated wick materials above the v-corrugated plate as illustrated in Fig. 5a. The results show that the modified SS with the PCMs under the v-corrugated plate with a smaller amount of water mass in basin realize the best performance among other studied configurations. The daily distiller yield of the SS with the PCMs when the water mass in the basin was about 25 kg was 12% and 11.7% larger than those for the corrugated plate SS without PCMs and with PCMs using wick materials, respectively, as illustrated in Fig. 5b. Furthermore, the cost estimated per liter of fresh water produced by the SS with PCMs using wick materials, with PCMs only, and without PCMs are estimated as 0.095, 0.08369 and 0.07182 $/l, respectively.

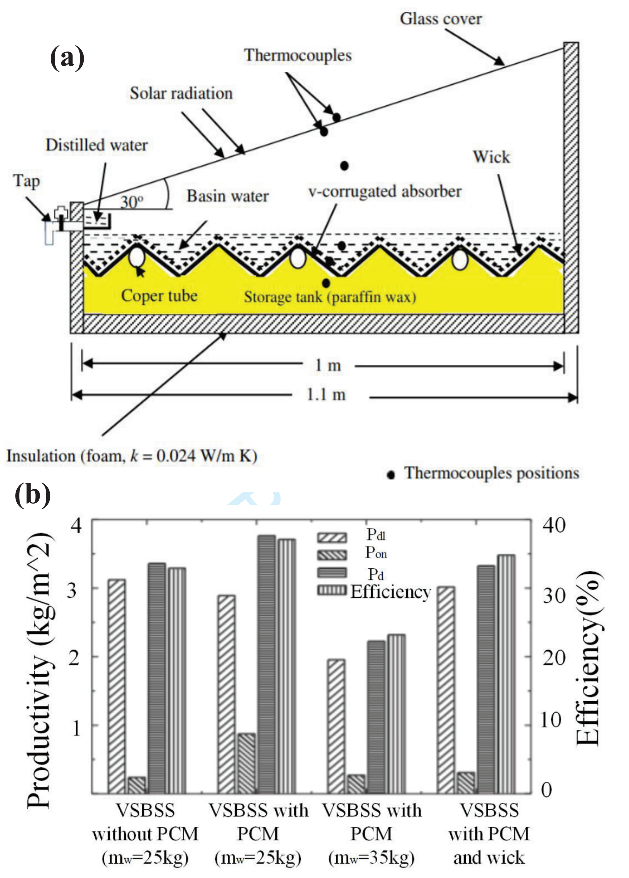

Fig. 5. (a) Schematic view of v-corrugated basin SS integrated with PCMs and (b) comparison of the efficiency and productivities of the examined SSs under various conditions [74].

Kabeel et al. [75] enhanced the performance of a modified pyramid solar still (MPSS) by using v-corrugated absorber plate and PCMs as illustrated in Fig. 6b, and compared its performance with the conventional pyramid SS as illustrated in Fig. 6a. The results illustrated that the accumulated output yield for MPSS with PCMs is larger than that of CPSS approximately by 87.4 % as illustrated in Fig. 6c. Furthermore, the improvement in the daily efficiency of MPSS with PCMs only and PCMs with v-corrugated absorber plate were 86.41% and 88%, respectively, compared with those of the CPSS. On the other hand, the cost estimated per liter of fresh water produced for MPSS and CPSS were 0.0236 and 0.0262 $, respectively.

Arunkumar and Kabeel [76] examined a concentric circular tubular solar still (CCTSS) integrated with parabolic concentrator (PC) and PCMs. The experiments are carried out with and without PCMs in the CCTSS. The PCMs (Paraffin wax) is filled into tubes (0.45 kg per tube) in the circular trough of the tubular SS. The results illustrated that the distiller water output of CCTSS- CPC with and without PCMs were 5.779 L/m^2/d and 5.330 L/m^2/d, respectively. Furthermore, the PCMs improved the yield by about 8%.

Radhwan [77] conducted an experimental endeavor in a stepped SS with PCMs (paraffin wax). The results illustrated that the stepped SS with paraffin wax has large efficiency (about 57%) and the output water was 4.6 L/m^2/d. Sathyamurthy et al. [78] experimentally investigated the effects of brine water depth on the triangular pyramid SS performance with and without PCMs (paraffin wax). The results illustrated that the triangular pyramid SS with PCMs has larger efficiency which increased by about 35% compared with SS without PCMs and the output water are 5.5 L/m^{2}d and 3.5 L/m^{2}d with and without PCMs, respectively.

Al-hamadani and Shukla [79] conducted an experimental study on a passive SS with PCMs (myristic acid) to test the influence of the mass of PCMs and brine water depth on the output distillate and the thermal efficiency of the system. The results illustrated that the larger mass of PCMs with lower brine depth in the SS basin significantly improves the daily output yield and efficiency, while as the PCMs exceeds 20 kg the output yield decreases. Therefore, the SS with PCMs improved the productivity output by 35–40%. Al Hamadani and Shukla [80] conducted experimental investigations on a SS with lauric acid as PCM. The results illustrated that larger value of PCM with smaller value of brine depth in SS improves the thermal efficiency and output distillate. The freshwater output of the SS with PCM was improved by about 127%.

Sarhaddi et al. [81] carried out an experimental and numerical simulation and a comparative study of energy and exergy analyses of two weir type cascade SSs with and without PCMs in semi-cloudy and sunny days as illustrated in Fig. 7. The governing equations of energy analysis for the different components of a SS (i.e., glazier cover, brine water, basin plate, PCMs) were obtained. Furthermore, exergy analysis for the different components of the SS was conducted. The results illustrated that the energy and exergy without PCMs is larger than that of the SS with PCM storage in sunny days. But, the SS with PCMs is better for semi-cloudy days due to its energy storage. The energy and exergy efficiencies of the SS without PCMs for a typical

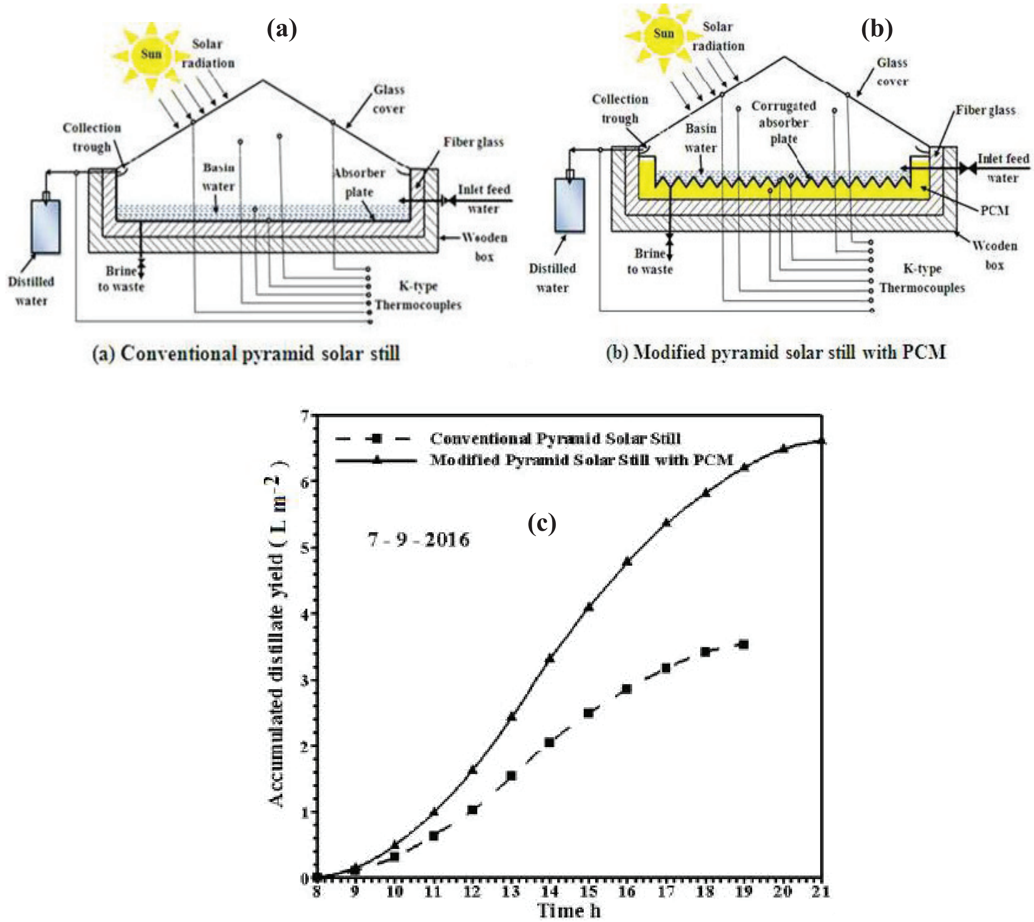

Fig. 6. Layout of (a) conventional pyramid SS (b) modified pyramid SS with PCM and (c) Accumulated freshwater for modified pyramid SS with PCM and conventional pyramid SS [75].

sunny day were 76.6% and 6.5%, respectively as illustrated in Fig. 7b; while the energy and exergy efficiencies of the SS with PCMs for a semi-cloudy day were 74.3% and 8.5%, respectively, as illustrated in Fig. 7c.

Sharshir et al. [82] experimentally investigated four modifications to improve the productivity of SSs; these modifications are: (modification A) the effect of using the flack graphite nanoparticles, (modification B) phase change material (PCM) with flack graphite nanoparticles, (modification C) flack graphite-water nanofluid with glass film cooling and PCM with graphite nanoparticles and glass film cooling (modification D) as illustrated in Fig. 8a. Moreover, they studied the influence of saline water depth of (0.5, 1, and 2 cm) on the performance of system (A) and system (B). The obtained results revealed that the best output yield is obtained for 0.5 cm water depth for all SSs. The last four modifications carried out at the same concentration 0.5% of flack graphite-water nanofluid. The productivity of modified (A), (B), (C) and (D) SSs was enhanced by about 50.28%, 65.00%, 56.15% and 73.80%, respectively, as illustrated in Fig. 8b.

Methre and Eswaramoorthy [83] conducted experiments to investigate the influence of nano-composite PCMs on the SS performance as. Paraffin wax mixed with Al_2O_3 nano materials (50 nm with two concentrations 2% and 4% for Nano PCM-1 and Nano PCM-2, respectively). The thermo-physical properties of nano-composite PCMs are also investigated. Exergy balance equations for saline water, basin liner, glazier cover, and thermal energy storage are derived to analyze the exergy efficiency with nano-composite. It was obtained that the SS exergy and energy efficiencies are enhanced using larger weight fraction ratio of Al_2O_3 nanoparticles (nano PCM-1 (2%) and nano PCM-2 (4%)), respectively, compared with those of paraffin wax only. Furthermore, the daily average productivity, energy efficiency, and exergy efficiency are found to be 4.17 L/day, 30.42% and 4.93%, respectively.

Kabeel and Abdelgaied [84] conducted experiments to investigate the influence of modified SS joined with loop of oil from cylindrical parabolic collector and PCM beneath the basin. The output water of the developed SS was improved by about 140.4 % compared with CSS but the developed SS daily efficiency was about 25.73%; whereas, conventional SS was about 46% this is due to the large area of the collectors.

Cheng et al. [85] studied the effect of a new shape stable PCM with high solar absorption and high thermal conductivity on the performance of SS via conducting simulation and experimental study. The new PCM has a solar absorption of 0.94 and the thermal conductivity of 1.50 W/m K.

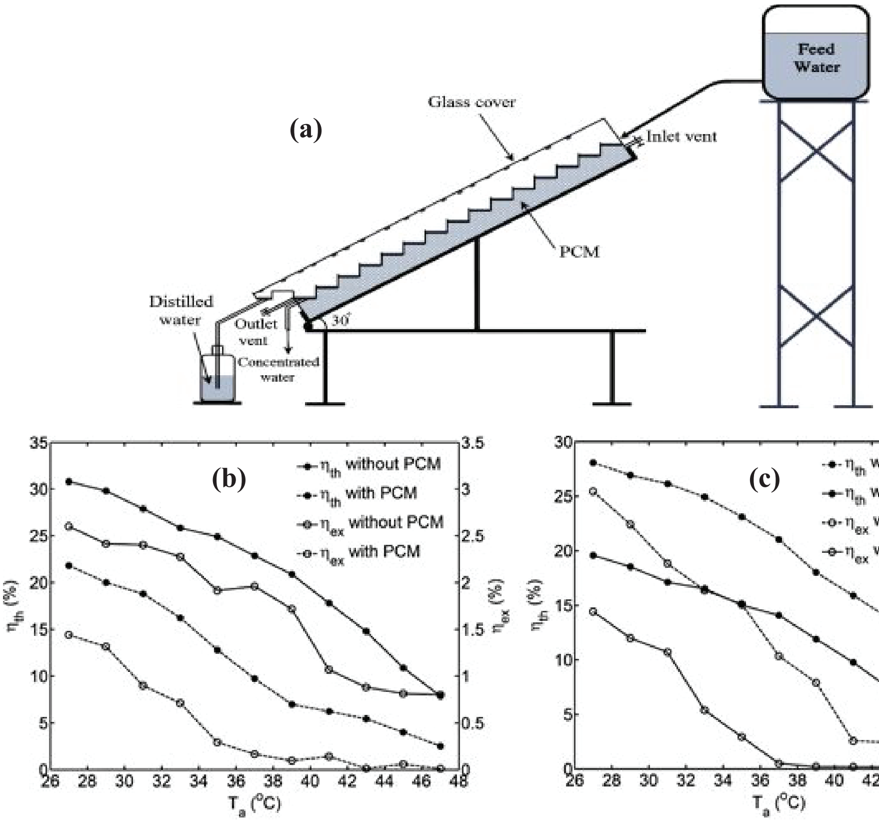

Fig. 7. (a) Schematic view of a cascade SS, (b) energy and exergy efficiencies of the SS without PCMs for a typical sunny day and (c) energy and exergy efficiencies of the SS with PCMs for a sample semi-cloudy day [81].

The authors examined the influence of melting temperature of the new PCM as well as thermal conductivity on the SS productivity. The experimental results illustrated that the daily freshwater productivity of the SS with PCMs was improved by about 43.3% compared with CSS. However, the results of simulation illustrated that the daily freshwater was improved by about 42% and 53% with thermal conductivity of 0.2 and 4 the W/m K , respectively compared with CSS. Also, when melting temperature of PCM increases from 34 up to 50°C the freshwater will be improved from 21.5 up to 57.5%, respectively. Lastly the cost per one liter of the freshwater was about 0.0243 and 0.0298 $ for CSS and modified SS respectively.

Al-harahsheh et al. [86] conducted experimental study on the effect of using PCM on the performance of a SS integrated with a solar collector. The PCM was heated thorough two sources; the first one was directly from the basin of the SS, and the second one used the hot water come from the solar collector which pass through heat exchanger immersed in the PCM. Moreover, the authors studied the effect of cooling, hot water and water depth on the freshwater output. The results illustrated that the freshwater improved by increasing the hot water as well as ambient temperature. The optimal cooling water rate over the glass was about 10 ml/s and the maximal freshwater can obtained at the lowest water depth. The capacity of the system was 4.3 ml/m^2 day, which produced about 40% during the night time. Arunkumar et al. [87] studied experimentally the effect of stainless-steel substrates, which are coated with copper oxide utilizing thermal evaporation method. The influence of stainless-steel coated with copper oxide combined with sponges type Polyvinyl Alcohol was done during four steps namely; CSS, CSS with stainless-steel coated with copper oxide, CSS with sponges, and CSS with stainless-steel coated with copper oxide and sponges. Four similar CSS were manufactured with basin area of 0.50 m^2 to investigate the four systems at the same time. The efficiencies of the four systems were, respectively, 37.0%, 53.0%, 32.0% and 41.0%, also the freshwater was 2.14, 2.99, 1.97 and 2.31 L/m^2/d.

Kabeel et al. [88] investigated the effect of PCM integrated with graphite microparticles on the performance of a SS. Two SSs were designed and manufactured to compare the performance of the still with and without PCMs. The first one was CSS and the second was CSS with PCMs and graphite microparticles. Furthermore, the authors studied the effect of mass concentrations of graphite microparticles on PCM properties. The experimental data illustrated that the freshwater output was up to 7.1, 7.9 and 8.5 L/m^{2}d at 0.0, 10 and 20% graphite microparticles mass concentration, respectively, while the CSS gives about 4.4 L/m^2 day. In addition, the thermal efficiency was about 51.4%, 59%, and 65.1% at 0.0%, 10%, and 20% graphite microparticles mass concentration, respectively, and the thermal efficiency of CSS was 32.2%. Yousef and Hassan [89,90] studied the effect of PCM on the performance of CSS and provided a comparative study between different methods to enhance system performance. In this regards, the first method was

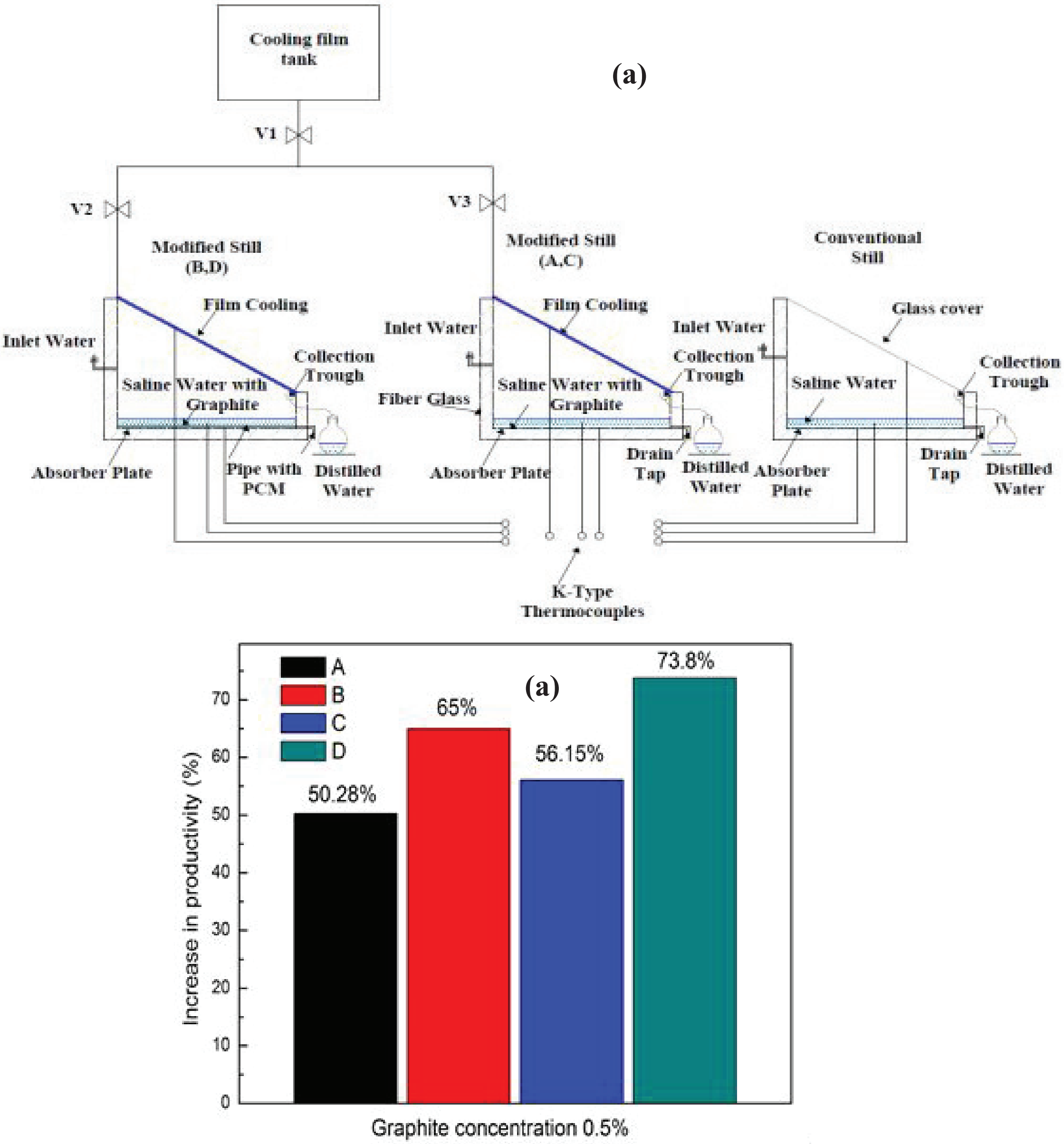

Fig. 8. (a). Schematic diagram of the experimental setup (b) increase in productivity of different modifications (A,B,C and D) [82].

performed based on PCM only, while in second one, the PCM was integrated with hollow cylindrical pin fins, and in the third method, the PCM is utilized with steel wool fibers. The last method, the SS was combined with only steel wool fibers. The results illustrated that the second solution was the best one, which give a better performance of PCM based pin finned, where the total freshwater was higher than the first one by about 7% and almost 17% compared to CSS.

Abu-Arabi et al. [91] used PCM (Sodium thiosulfate pentahydrate) for energy storage applications during the daytime and releasing this energy during the night time. The paper experimentally investigated the effect of PCM material on the performance of the SS. The obtained results indicated that with the increase of the amount of PCM, freshwater output will be reduced. For instant, the freshwater was decreased by about 30% when the PCM to water mass ratio increases from 10 to 100%. But the large amount of PCM make the basin with large temperature for long time. So, this way is found to be useful for supply the hot water during the nighttime. Rufuss et al. [92] examined the influence of improving the thermal properties of PCM by using three types of nanoparticles namely: CuO, TiO_2 and GO with 0.3% wt concentration on the SS productivity and the results were compared with the CSS. Four SS were designed and manufactured to compare the performance of the SS with and without PCM. Further, the authors studied the effect of PCM with nanoparticles on freshwater production, temperature of water, and storage temperature. The results illustrated that the freshwater output was about 5.28, 4.94 and 3.66 L/m^{2}d for the SS integrated with PCM and CuO, TiO_2 and GO respectively. While the output freshwater for the CSS was about 3.92 L/m^{2}d.

3. Solar still with sponge's cubes as a TESMs

Abu-Hijleh and Rababa'h [93] investigated the influence of using sponge cubes on the SS performance. The evaporation rate was increased due to the considerable increase in the surface area which reinforced by sponge cubes. Keeping the sponge cubes in the basin causes an increase in the SS output by about 273% compared with that of CSS.

Murugavel et al. [94] studied the SS with different materials such as cotton, jute, cloth, porous materials, and sponge sheet. The obtained results revealed that the highest yield is achieved using black cotton cloth. El-Sebaii et al. [95] applied a thin-layer of a storage material beneath the basin plate of an active SS to produce potable water after sunset and investigated the SS performance.

Samuel et al. [96] Fig. 9a illustrated the different types of low-cost energy storage material to enhance the fresh water yield in a SS: for example b) ball-shape; c) sponges as a heat storage. They experimentally and theoretically investigated the performance of the SS. The results showed that the yield of fresh water using salt as a heat storage material and sponge reaches a maximum productivity of 3.7 and 2.7 L/m^{2}d, respectively, compared with 2.2 L/m^{2}d without using any storage material. Also, they concluded that the use of spherical ball heat storage in a SS gives low cost of the produced water.

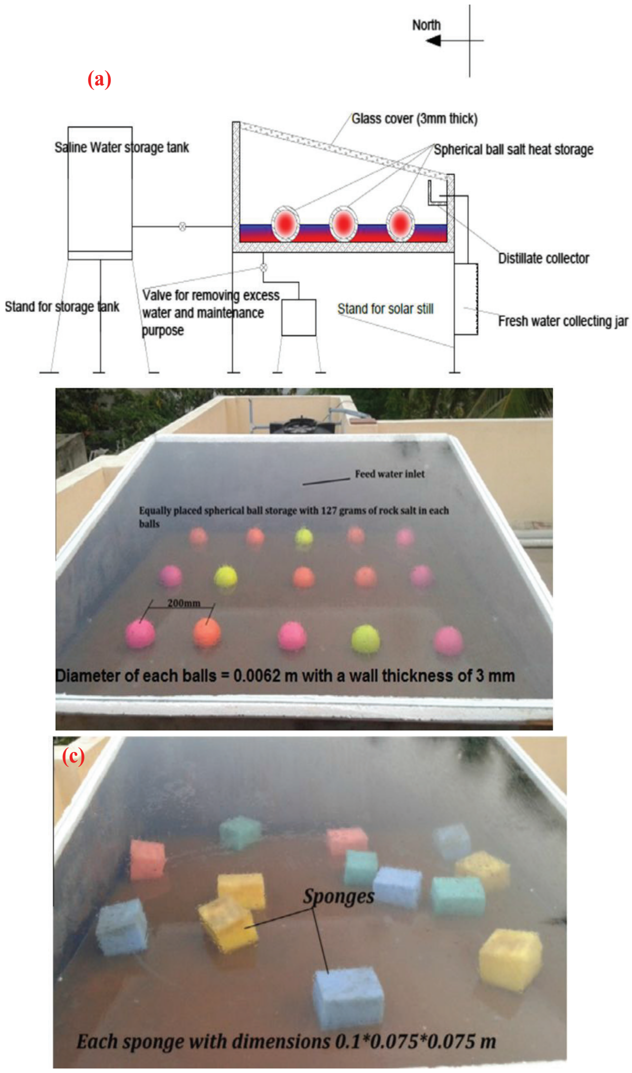

Fig. 9 a) Diagram of a SS with; b) ball-shape; c) sponges as a heat storage [96].

4. Solar still with gravels and sand as a TESM

Nafey et al. [97] investigated the effect of using black gravel and black rubber on the yield of a SS. They investigated the distilled water yield of the SS using black gravel of various sizes (ranged from 7 to 30 mm) and black rubber with various thicknesses (ranged from 2 to 10 mm) at different brine volumes (ranged from 20 to 60 L/m^2). The productivity was increased by 20% using black rubber of 10 mm thickness at brine volume of 60 L/m^2. This may be referred to the ability of black rubber to absorb and release the solar energy slower than the black gravel. Additionally, the productivity was increased by 19% at brine volume 20 L/m^2 using black gravel of 20–30 mm size. This is because of the big amount of the solar energy which may be absorbed by the large gravel sizes.

El-Bialy [98] experimentally studied a passive SS with a floating absorber. Two SSs were designed, manufactured to compare the performance of the still with and without floating absorber. The first one is CSS and the second is modified still (CSS with floating absorber). Furthermore, the influences of the amount of water and different types of absorber plate on the performance of SS were investigated. The results illustrated that the modification causes a large enhancement in the productivity. The different types of floating absorbers such as copper, stainless steel, aluminum and mica were used as good materials for enhancing the SS productivity by 17.2%, 15.2%, 20.1% and 42.2.1%, respectively.

Sakthivel and Shanmugasundaram [99] made an attempt to use maximum solar energy and decrease heat loss from sides and basin plate. The traditional SS is integrated with an energy storage (black granite gravel) with the size of 6 mm provided in the basin to various depths. Black granite is used as a means of storing energy as well as an insulating layer to decrease the loss of side and bottom. Black gravel is used to absorb excess thermal energy from solar radiation through the sunrise and the noon period. As a result, the heat accumulated in the distance between the water surface and the glass surface is reduced, thus increasing the temperature difference between the water surface and the glass. The depth (amount) of the gravel layer will affect the water temperature, basin temperature and glass temperature which will affect the productivity as well as solar still performance. The results illustrated that SS through adding a black granite gravel as an energy storage material and the productivity was enhanced by 17–20%. Furthermore, black granite gravel is too cheap.

Abdallah et al. [100] enhanced the performance of SS by using various sorts of absorbing materials such as coated and uncoated porous media and black rocks as absorbing materials and compared the results with using both coated and uncoated metallic wiry sponges. The results illustrated that the uncoated sponge has the largest freshwater production during the day, where the black rocks have a medium freshwater output finally the low freshwater production come from coated metallic wiry sponges. Furthermore, the average total gain in the collected distilled water was 60%, 43% and 28% for the black rocks, non-coated mineral spills and coated, respectively.

Panchal [101] experimentally studied the use of different heat storage beds (calcium, black gravel and stones pebbles) at 2 cm brine depth to enhance the SS performance. The results illustrated that the freshwater output of the SS with calcium stones is larger by about 74% compared with that of pebbles and black gravel. Panchal [102] conducted an experimental study on a double basin SS integrated with heat storage materials (Black granite gravel) as well as vacuum tubes which used to improve the freshwater output by decreasing the amount of impure water in the basin; and compared its performance with the conventional double basin SS without black gravel and vacuum. The results illustrated that, the daily fresh water productivity was improved by 65%, when black gravel integrated with vacuum are used, compared with conventional double basin SS.

Omara and Kabeel [103] experimentally studied the effect of different heat storage beds (yellow and black sand), with different heights (1,2,3 and 5 cm) as well as different brine depths over the sand layer (1, 2 and 3 cm), on the SS performance. Results illustrated that the extreme daily distiller productivity of sand beds SSs is obtained at sand layers height of 1 cm with zero height of brine depth over the sand layer, it was found that the use of yellow sand layers and black sand layers in the SS improves the freshwater productivity by 17% and 42%, respectively, compared with that of the CSS. Furthermore, the daily thermal energy efficiency of yellow and black sand layers SSs and CSS are 39%, 49% and 35%, respectively. The cost estimated per one liter of the yield for, yellow and black sand layers SS and CSS are approximately 0.043, 0.037 and 0.049$, respectively.

Sathyamurthy et al. [104] conducted a mathematical and experimental investigation to improve the performance of a CSS with heat storage materials (sand in cuboidal boxes). The fresh water output from SS with sand was enhanced by 145% compared with that of CSS. The total fresh water output from the SS with and without sand was about 5.1 and 1.9 L /m^{2}day, respectively.

5. Solar still with aluminum filling as a TESM

Abdullah [105] conducted an experimental investigation on active stepped SS integrated with air heater as well as TESM (aluminum filling) to improve the overall performance. Results illustrated that, the freshwater productivity of stepped SS integrated with TES improved by 53% compared with that of CSS; while the freshwater productivity of stepped SS integrated with air heater and film cooling improved by 112%. Furthermore, the daily efficiency for CSS and stepped SS without any modifications are about 34% and 48%; respectively; whilst it is 59% , 52% and 55% for glass cooling, hot air, and TESM, respectively.

6. Summary

Table 1 shows the differentiation of various kinds of SSs with different types of TESM which used for improving the production of distillate water from brackish or sea water. The stills with TESM have charming influence rely on their own utilities and for which they have been applied. In Table 1, differentiation on three topics have been performed, i.e. reference, type of TESMs, and the main results.

It is worth to mention that PCM utilization in SS depends on the latent heat of the PCM, as the absorption and releasing of heat occurs via phase change of the PCM from solid state to liquid state or vice versa. However, for other TESM (such as gravel) the absorption and releasing of heat occur via rising the temperature of the material exploiting the heat capacity of that storage medium. In other words, PCM is used as a latent heat storage medium, while gravel, sand, and aluminum filling are used as a sensible heat storage medium. For latent heat storage materials, melting temperature, specific heat capacity, density, and latent heat are the most important thermophysical properties that should be taken into consideration during the selection of latent heat storage material for a certain application. While for sensible heat storage materials, specific heat capacity and density are the most important thermophysical properties as tabulated in Table 2.

7. Conclusions and prospective

In recent years, the TESMs have been widely used in order to store energy during the day (sun's brightness) and utilize this stored energy during the night to improve the productivity as well as the performance of the SS. In this paper, we summarized the work done on SSs using TESMs to improve their performance. The main results/conclusions are highlighted as follows:

- The productivity was increased by 108% using paraffin wax and forced hot air bubble compared with the CSS.
- The productivity of the SS using black rocks was increased by 17–20%.
- The productivity was enhanced by 67.18% by using paraffin wax compared with the CSS.
- The stepped SS with paraffin wax had large efficiency (improved by about 57%) and the water yield was 4.6 L/m^2/day.
- The productivity was increased by 20% using black rubber of 10 mm thickness at brine volume 60 L/m^2
- The productivity of the SS was increased by 19% using black gravel of 20–30 mm size at brine volume of 20 L/m^2.
- The yield of fresh water using salt as a heat storage material and sponge reached the maximum productivity of 3.7 and 2.7 L/m^2, respectively, compared to 2.2 L/m^2 for CSS.
- The sponge cubes in the basin water caused an increase in the SS output by about 273% compared with CSS.
- The fresh water output from SS with sand was enhanced by 145% compared with CSS.
- The daily efficiency for CSS and stepped SS without any modifications were about 34% and 48%, respectively; whilst it was 59%, 52% and 55% for glass cooling, hot air, and TESM, respectively.

Table 1
Summary of some kinds of SSs with different types of TESMs which used for enhancing the production of SSs

References	Types of TESM	Main results/summary
El-Sebaii [65]	Paraffin wax	The productivity during the daytime was enhanced by about 80% with PCM compared with the CSS.
Kabeel and Abdelgaied [66]	Paraffin wax	The productivity was enhanced by 67.18% by using PCM compared with the CSS.
Kabeel et al. [67]	Paraffin wax	The productivity was increased by 108% compared with the CSS.
Ramasamy and Sivaraman [68]	Paraffin wax	The output distillated was increased by 10.11% compared with the CSS
Kabeel et al. [70]	Paraffin wax	The daily output yield in summer season was enhanced by about (55–65%) and was enhanced in winter season by about (35–45%) compared with the CSS.
Ravishankar et al. [71]	Paraffin wax	The use of PCM improved the distillate water of SS by about 20%.
Kantesh [72]	Bitumen	The use of Bitumen improved the distillate water by about 2%.
Shalaby et al. [74]	Paraffin wax	The daily distiller yield of the SS with PCMs when water mass in the basin about 25 kg was 12% and 11.7% larger than those for the corrugated plate SS without the PCMs and with the PCM using wick materials.
Kabeel et al. [75]	Paraffin wax	The accumulated output yield for MPSS with PCMs was larger than that of CPSS approximately by 87.4 %.
Arunkumar and Kabeel [76]	Paraffin wax	The PCMs improved the yield by about 8%.
Radhwan [77]	Paraffin wax	The efficiency of stepped SS with paraffin wax was about 57% compared with CSS
Sathyamurthy et al. [78]	Paraffin wax	The output water was improved by about 57.14% compared with CSS
Al-hamadani and Shukla [79]	Myristic acid	The freshwater output for SS improved by 127% using PCMs.
Sharshir et al. [82]	Paraffin wax	The productivity of modified SS with PCM, graphite nanofluid and glass cooling was enhanced by about 73.80%.
Abu-Hijleh and Rababa'h [93]	Sponge cubes	The sponge cubes in the water of basin caused an increase in the SS output by about 273% compared with CSS.
Samuel et al. [96]	Ball-shape salt sponges	The yield of fresh water using salt as a heat storage material and sponge improved by 68% and 22.7% respectively.
Nafey et al. [97]	Black gravel and black rubber	The productivity was increased by 20% using black rubber of 10 mm thickness at brine volume 60 L/m^2
		The productivity was increased by 19% at brine volume 20 L/m^2 using black gravel of 20–30 mm size
Abdallah et al. [100]	Coated and uncoated metallic wiry sponges	The SS productivity using black rocks was increased by 17–20%.
Panchal [101]	Calcium, black gravel and stones pebbles	The freshwater output of the SS with calcium stones was larger by about 74%.
Panchal [102]	Black granite gravel	The daily fresh water was improved using black gravel and vacuum by 65% compared with conventional double basin SS.
Omara and Kabeel [103]	Sand yellow and black	The daily fresh water output of yellow and black sand layers was improved by about 42% and 17% respectively.
Sathyamurthy et al. [104]	Sand in cuboidal boxes	The fresh water output from SS with sand was enhanced by 145%
Abdullah [105]	Aluminum filling	The fresh water output from SS with aluminum filling was enhanced by 53%

- As it is clear from the paper that all TESMs have different rates of improvement in productivity and efficiency of SSs. From this review, the best type was sponge cubes in the basin water caused an increase in the SS output by about 273% compared with CSS and this followed by PCMs. These various types of TESMs depends on different factors such as meteorological data and operating parameters, cost, etc. So, the authors recommend using the available types in the market with reasonable cheap price.

In the future, we believe that amelioration in the SS performance may be achieved by integrating different types of PCMs with different nanomaterials.

Table 2
Illustrate some thermal properties of the TESM

Properties energy storage material	Thermal conductivity (W/m K)	Melting Temperature (°C)	Specific heat capacity (J/kg °C)	Density (kg/m^3)	Latent heat (kJ/kg)
PCMs	0.24	48–65	2510	760	226
Sponge's cubes	Porosity	Not given	700	500	Not given
Gravels	Gravel dry 0.4	Not given	850	2800	Not given
	Gravel saturated 2.4				
Sand	Sand, dry 0.4	About	800	1800	Not given
	Sand, dry –0.15–0.25 sand saturated 2–4	1650	1483	1730	
			1747	1444	
	Sand, moist 0.25–2		800	1600	
	Sand stone 1.7		1632	1613	
Aluminum filling	200	660	900	2700	397
Black rubber	Rubber, cellular 0.045 Rubber, natural 0.13	180	2100	1522	Not given

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