Experimental investigation of a solar still equipped with an external heat storage system using phase change materials and heat pipes

Meysam Faegh^a, Mohammad Behshad Shafii^{a,1}

Abstract

In this study, a novel idea of storing the latent heat of condensing vapor in solar stills by means of phase change materials (PCMs) as a thermal storage is experimentally investigated. During the daytime, the generated water vapor by the solar energy, is conducted to an external condenser filled with PCM to be condensed. The wasted latent heat is absorbed by PCM and thereby stored. It is worth noting that there is no direct contact between the saline water and the PCM, therefore, the solar energy is not directly stored in the PCM. In the evening, the energy stored in the PCM is transferred as heat to the saline water by heat pipes and enables the desalination process to continue. Several tests were run to investigate the performance of the system. The results revealed that the presence of an external condenser filled with PCM and equipped with heat pipes in a solar still with evacuated tube collectors, makes the desalination process continue after the sunset without causing a decrease in the yield during the daytime. The yield increases by 86% as compared to the yield of the system without PCM and reaches to 6.555 kg/m²day with the efficiency of 50%.

Keywords: Evacuated tube collector, Heat pipe, Phase change material, Latent heat storage, Solar still

1. Introduction

The rapid population growth and industrialization of societies has led to a disequilibrium between the supply and demand of the fresh water [1]. Desalination of the saline seawater is an efficient technique for fulfilling the demand for fresh water. From past times several techniques have been innovated for desalination. Currently, the most prominent processes for desalination are reverse osmosis [2], membrane distillation [3], multistage desalination [4], multiple effect distillation [5], and electrodialysis [6], which rely on fossil fuels. Contamination of the environment by fossil fuels and engagement of the whole world with the energy crisis underscores the necessity for using renewable energy sources in various fields such as desalination. Solar stills, which have two features of being environmentally-friendly and using the sun as a free and available source of energy, are effective systems for desalination especially in remote areas [7]. The basis of the operation of all solar stills is the absorption of solar energy by the saline water, its evaporation and then its distillation and collection as fresh water.

The main disadvantage of solar stills is their low yield as compared to other desalination systems. Therefore, several studies have been conducted to enhance the performance of these systems. An exhaustive review of

the studies conducted to increase water yield and efficiency in solar stills are given in [8, 9]. Different studies show that increase in the average water temperature, and as a result, increase in the yield of solar stills is possible through addition of solar collectors to these systems [10, 11]. Evacuated tube collectors have the characteristic of sun tracking as a result of their cylindrical structure. Furthermore, they have lower heat loss due to the vacuum between the two glass walls, and as a result, have higher performances in comparison with the flat-plate collectors. In these evacuated tubes, either water is directly injected inside the collector or the thermosiphon heat pipe is used to transfer the heat absorbed from the sun to the outside [12]. To increase the efficiency of the solar still, Singh et al [13] studied a model of a solar still equipped with the evacuated tubes in which the water was directly present inside the collector. They calculated the maximum yield and efficiency as 3.8 kg/m² and 33%. Jahangiri Mamouri et al. [14] experimentally investigated the performance of a solar still with evacuated tubes and used the heat pipe for the transfer of the heat absorbed from the collector interior to the water basin. The maximum efficiency and hourly yield of 22.9% and 1.02 kg/m²hr were obtained. Recently, Jafari Mosleh et al. [15] has reached the maximum efficiency of 65.2% by using the evacuated tube and sun tracking system together in a solar still.

One of the disadvantages of solar stills is the waste of latent heat of condensation from the upper glass to the environment [16, 17]. For this purpose, several studies are conducted to reduce such wastes. Madhlopa and Johnstone [18] numerically evaluated the performance of a solar still with a three-stage external condenser. They prevented the waste of the heat released from distillation on each stage of the condenser by transferring it to the upper water basin, and enhanced the performance of the system up to 62% in comparison to a simple solar still. Monowe et al [19] theoretically investigated the effect of the presence of a fan inside the evaporation chamber used for transferring the vapor generated to an external condenser to transfer the heat inside it to a secondary stream. The heat stored by the secondary stream in the heat exchanger has the capability to be used for domestic consumption or for system performance in case no sunshine exists. The efficiency of the system can increase up to 77% and 85% in each case. Karimi Estahbanati et al [20] examined the performance of a multi-effect solar still and concluded that the increase in yield is in conjunction with the increase in the number of stages in the continuous mode. Recently, Shafii et al [21] reached the efficiency of 52% by preventing the waste of latent heat of distillation and its recycling by thermoelectric modules which results in the generation of electricity.

Since the solar stills produce water only during the daytime, several studies have been conducted to store energy during the daytime and using it to produce water at night. Part of the heat can be stored as sensible heat in Jute cloth [22], sand [23], charcoal particle [24], and quartzite rock [25]. These materials are located inside the water basin as energy absorbers, and bring about absorption of a portion of the solar energy during the daytime and restore it to the water at night. However, they did not lead to a significant increase in the yield. On the contrary, the latent heat storage systems boast advantages in comparison with sensible heat storage systems such as having higher stored energy density and also storage of the latent heat at the roughly constant

67 phase change temperature [26]. El-Sebaai et al [27] mathematically modeled the performance of a single slope-
68 single basin solar still by placing phase change materials beneath the water basin to prevent heat waste from
69 the lower section of the basin. In the system they studied, a portion of the energy absorbed by the basin water,
70 melts down the phase change material, and as a result, a considerable amount of the heat is stored in the phase
71 change material instead of being wasted. In the evening, by the decline in the system temperature, the phase
72 change material freezes and the heat released from it is transferred to water. Consequently, the desalination
73 process continues until a few hours after the sunshine. Their results revealed that by storing heat inside the
74 phase change material, the amount of water produced in one day is 1.8 times that of the case without a storage
75 system. Arunkumar et al [28] increased the yield up to 26% by placing the phase change material inside metal
76 balls and placing them inside the water basin. Sathyamuthy et al [29] experimentally investigated a solar still
77 by separating the evaporation and distillation chambers and placing the phase change material between them.
78 The use of phase change material led to the storage of a portion of the solar energy in it. By restoring this
79 energy, it brought about a 52% increase in the yield and the efficiency of 14%.

80 Up until now the research into solar stills in which the phase change materials are used are such that the phase
81 change materials store a portion of the radiative energy of the sun during the daytime and this stored energy is
82 used for desalination at night. Therefore, due to the use of a portion of the energy for desalination during the
83 daytime and storage of the remainder for the use at night, considerable decline in the yield is observed during
84 the daytime.

85 The goal of the present study is to design a novel solar still by using an external condenser filled with PCM
86 which can increase the total yield during a day without causing a reduction during a daytime by recycling the
87 latent heat of vaporization and storing it. To achieve this goal, it is necessary to prevent the saline water to
88 contact the phase change materials and use the whole radiated energy to evaporate the saline water during the
89 daytime. During the daytime, the vapor produced by the solar radiation is conducted to an external condenser
90 filled with PCM to be condensed. The wasted heat of vapor in the condenser is absorbed by the phase change
91 material and is then stored. Therefore, the storage of energy inside the phase change material is only through
92 the vapor and its condensation inside the phase change material, and the solar energy is not directly stored in
93 the phase change material. The thermosiphon heat pipes have the distinguishing characteristic of transferring
94 heat from down to top, hence act like a thermal diode, and therefore, are suitable choices for our purpose. In
95 other words, by placing the thermosiphon heat pipes between the saline water on the top and the phase change
96 material tank on the bottom, only heat transfer from down to top is possible. In hours when there is no radiation
97 (when the temperature of the saline water is colder than that of the phase change material), the thermal energy
98 is transferred from the storage system to the saline water and the desalination process continues in the absence
99 of solar radiation. However, during the daytime (when the temperature of the saline water is higher than that
100 of phase change materials), the heat absorbed from the sun does not transfer to the storage system beneath it
101 (due to the operation of the heat pipe as a thermal diode), and as a result, is solely used for the evaporation

process during the radiation. In addition, evacuated tube collectors are also utilized to maximize the increase in water temperature. In this study, the effect of the presence of an external heat storage system equipped with heat pipes and phase change materials on the yield rate is experimentally investigated.

2. System Description

All experiments are conducted in Tehran (latitude: 42.35, longitude: 35.51, and elevation: 1172 m). The experimental setup has two different mechanisms for the daytime and night. Schematic of the system is given in **Fig. 1**. The system consists of two evacuated tube collectors, a saline water basin, a tank for phase change material, a fan, and also twenty thermosiphon heat pipes. Paraffin is used as the phase change material due to its high latent heat, reasonable price, and accessibility [30, 31]. Further details regarding the sizes of different parts are given in **Table 1**. At the beginning of the daylight, the saline water is directly injected inside the evacuated tube collectors and basin (until the height of 2 cm from the basin bottom). In the upper section of the saline water, a glass with the angle of 35.5 degrees—which equals Tehran’s latitude—is placed. It is worth mentioning that several studies have shown that the optimum value for the orientation angle of glass cover is the latitude of the test location [32]. The solar energy, which radiates to the collector surface and floor of the saline water basin, causes the temperature of the saline water to rise and the water to evaporate. A fan with the power of 7 W is used to conduct the vapor from the basin through the phase change material by suitable connecting tube. To prevent the heat waste of the vapor along the path between the basin and phase change material, the connecting tube is completely insulated by polyurethane of thickness 3 cm. As the vapor passes through the copper tubes inside the phase change material, its temperature reduces resulting in condensation into the fresh water which is collected from the bottom. During the daytime and by increase in the solar radiation, the temperature of the vapor entering the tank of the phase change material increases and causes the temperature of the phase change material to rise. When a PCM is heated initially it behaves like sensible heat energy storage and the materials temperature is increased. However, once the transition temperature is reached the material will continue to absorb heat as latent heat at a constant temperature while it changes state.

Thermosiphon heat pipes are heat transfer devices with high conductivity which transfer heat only in one direction from down to top [33]. In the evening, by a decline in the solar intensity and saline water of the basin, the energy storage system which is composed of phase change material with a higher temperature as compared to the basin water, begin to transfer the stored heat to the saline water. The evaporative section of the heat pipes lies inside the phase change material and its condenser section is placed inside the saline water basin. The heat stored in the phase change material is absorbed in the evaporative section of the heat pipe and causes the working fluid inside it to evaporate. To retrieve the energy, the PCM changes back from the liquid to the solid phase and the energy stored as latent heat is released. Schematic of the operation of the thermosiphon heat pipe is shown in **Fig. 2**. The vapor in the heat pipe moves towards its upper section, transfers the stored latent heat of desalinated water from the PCM to the saline water in basin and the condensed liquid moves downward by gravity. The heat transferred to the saline water causes its temperature to rise, and as a result, enables the

137 evaporation process to continue. Therefore, the system continues to operate a few hours after solar radiation
 138 ends and the desalination process continues. It is worth mentioning that due to the operation of the heat pipe
 139 as a thermal diode, no heat is transferred from the water basin to the phase change material (from top of the
 140 heat pipe to its lower part) during the daytime, and therefore, the whole radiated energy is consumed for water
 141 evaporation. Due to the low temperature difference between the phase change material and saline water, the
 142 most suitable working fluid is the one which can generate the maximum heat transfer at these temperatures.
 143 Acetone is used as the working fluid due to its satisfactory performance in lower fluxes [34]. Since the
 144 operation of the heat pipe also depends upon its filling ratio, several tests were conducted to assess its
 145 performance under different filling ratios. **Fig. 3** shows the variations in the thermal resistance of the heat pipes
 146 vs input fluxes, tested for different filling ratios. As is observed, the filling ratio of 15% is associated with the
 147 lowest thermal resistance, and therefore, is used in manufacturing heat pipes.

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149 **Fig. 1** Schematic of the processes in the system with external condenser containing PCM and heat pipes (test 4), (a) charging
 150 process (b) discharging process.

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Table 1 Details of the dimensions and sizes of the equipment used.

Evacuated Tubes	Inner diameter = 4.7 cm
	Outer diameter = 5.8 cm
	Length = 180 cm
	Inclination Angle = 35.5
Water Basin	Area = 20 cm * 20 cm
	Wall thickness = 1 mm
	Insulation = Fiber glass with 3 cm thickness
PCM	Paraffin wax [26]
	Container dimensions = 25 cm * 25 cm * 35 cm
	Insulation = Fiber glass with 5 cm thickness
Heat Pipes	Copper tube, diameter of 1 cm
	Length = 40 cm (Evaporator=30 cm, Condenser= 2 cm)
	Working fluid = Acetone
	Filling ratio = 15%

Fig. 2 Schematic of the operation of the thermosiphon heat pipe.

Fig. 3 Thermal resistance of the heat pipes vs input power for different filling ratios.

3. Experimentation

The goal of the present work is to study the effects of using a latent heat storage system equipped with heat pipes, phase change materials and evacuated tubes to recycle the latent heat of distillation and increase fresh water yield such that it would be possible to continue production until hours of night without reducing the production during the daytime, unlike the conventional solar stills which have a storage system. To examine the distinct effect of the presence of external condenser filled with PCM and external condenser without any PCM and also its comparison with a simple solar still, four different tests were designed and conducted. Schematic of the tests is given in **Fig. 4**. In test 1, the system is similar to a simple solar still with evacuated tube collectors (ETC). To examine the effect of the presence of a heat storage system, in test 2, heat storage system is added to test 1 (named as the uninsulated cover glass system equipped with the external condenser (EC) filled with PCM) and vapor distillation takes place both on the cover glass and inside the storage system. Similar to test 1, the radiation enters the system both through the evacuated tubes and the cover glass. In this case, the heat is stored in paraffin during the daytime, and in the evening, the energy stored in the paraffin is transferred to the saline water in the basin through the heat pipes and enables the desalination process to continue. Since considerable heat is wasted through the upper glass in the solar stills [27], in test 3, despite tests 1 and 2 in which distillation took place over the glass, the upper glass is insulated and effect of insulation on the amount of the yield of system was examined. In fact, test 3 is similar to test 1 with the difference that the upper glass is insulated, radiation enters the system only through the evacuated tubes, and the whole

distillation process takes place in the external condenser (named as the insulated cover glass system equipped with the external condenser without PCM). Finally, test 4 investigates the simultaneous effects of glass insulation and the presence of an external latent heat storage system (named as the insulated cover glass system equipped with the external condenser filled with PCM). **Fig. 1** displays the functioning of the system during the charging and discharging process for test 4. The vapor generated inside the basin is conducted to the external condenser containing paraffin by a fan and the heat is transferred to it. In this way the whole heat released from the condensing vapor is stored in the paraffin. In the evening, the heat stored in the paraffin is transferred by the heat pipes to the basin above and enables the desalination process to continue.

All experiments were conducted at the dates of 16th to 19th August. The variations in the vapor temperature at collector outlet (T_1), water temperature inside basin (T_2), vapor temperature at basin outlet (T_3), vapor temperature at PCM tank inlet (T_4) and PCM temperature (T_5) were measured by type K thermocouples and recorded by Lotrun BTM-4208SD data logger. The installation places of the thermocouples are given in **Fig. 1**. At the same time, Apogee SP-110 pyranometer was used to measure the highest solar radiation perpendicular to the collector. It is worth mentioning that the tests were conducted in four consecutive days and the rate of solar radiation in the four experiments were close to each other. The rate of water yield is also measured every thirty minutes. The accuracy and expanded uncertainty of the measured parameters are given in **Table 2**.

Table 2 Resolution and expanded uncertainty of the measured parameters

Instrument	Resolution	Expanded uncertainty
Solar Intensity [W/m^2]	1	10.06
Temperature [$^{\circ}\text{C}$]	0.1	1.006
Yield [ml]	5	5.8

4. Results and Discussion

Fig. 5 shows the water yield in different hours and also the solar intensity for the test 4. The maximum water yield of $1.05 \text{ kg/m}^2\text{h}$ was obtained at 14:00 which has a thirty-minute delay with respect to the maximum solar intensity of 970 W/m^2 at 13:30. The delay is due to the high thermal mass of the system. It is worth noting that the installation of the latent heat storage system enables the water yield to continue until two hours after sunset (21:00). As is observed in **Fig. 5**, the amount of solar radiation on the evacuated collector tube is constant in a wide range of daytime hours which is the result of the cylindrical geometry of the collector and absorption of the perpendicular radiations of the sun in different daytime hours. However, the radiation in flat plate collector is perpendicular only at midday; therefore, the energy absorbed has higher variations in the hours before and after midday for flat plate collectors. In **Fig. 6**, the water yields at different times are shown for all four tests. According to **Fig. 6**, in test 1 which is associated with a basin and evacuated tube collectors, the vapor is condensed over the cover glass and the maximum water yield of $0.68 \text{ kg/m}^2\text{hr}$ is obtained. Test 2 is similar to test 1 except that the heat storage system is added to it. Nevertheless, since a portion of vapor is condensed on

217 the cover glass, the amount of waste heat recovery from distillation is low and the yields in the two tests of 1
218 and 2 are close to each other. Only a slight increase in the yield of test 2 after 17 p.m. is observed which is due
219 to the presence of heat storage system. In test 3, the cover glass is insulated and therefore the whole vapor is
220 condensed inside the external condenser without PCM. The comparison between test 1 and 3 shows that despite
221 a reduction in the input radiation to the system in test 3, due to the insulation of the cover glass, the amount of
222 water yield has a considerable jump and reaches the maximum amount of $1.025 \text{ kg/m}^2\text{hr}$ at 14:00. In test 4, the
223 external condenser of the test 3 is filled with paraffin as a PCM. By doing so, a heat storage system is added
224 to test 3. Therefore, virtually all the latent heat of vaporization is stored in the storage system and makes
225 desalination continue until 21:00. The comparison between tests 3 and 4 shows that the water yields for the
226 two tests are almost equal until 16:00. The reason is that heat pipes do not function as long as the saline
227 temperature is higher than the PCM temperature until 16:00.

228 Due to absence of a storage system in test 3 (an external condenser without PCM), from 16:00 onwards, the
229 amount of yield in the system reduces as compared with the device of test 4 which has the storage system and
230 operable heat pipes (external condenser filled with PCM). As was previously stated, the lowness of yield during
231 the daytime for test 2 in comparison with test 4 is due to the considerable wasted heat from the cover glass and
232 as a result, decrease in the vapor flow rate through the storage system. The wasted heat from the cover glass
233 has led to lesser energy storage in test 2, yet the insulation of cover glass in test 4 enables almost all the latent
234 heat of the generated vapor to get stored in the phase change material, and as a result, from 16:00 onwards,
235 more water is yielded in comparison with test 2. In fact, although in both tests 2 and 4 a storage system exists,
236 the wasted heat from the cover glass in test 2 has led to the flow of vapor with lower temperature through the
237 storage section, and hence, heat is only stored as sensible. In test 4 the heat is stored both as sensible and as
238 latent and hence more yield resulted.

Fig. 4 Schematic of the tests conducted

Fig. 5 Hourly water yield and solar intensity for the system with latent heat storage system (external condenser filled with PCM) (test 4)

Fig. 6 Hourly water yield for different tests

The cumulative water yield for all four tests are given in **Fig. 7**. It is observed that the insulated cover glass system equipped with the external condenser filled with PCM (test 4), followed in descending order by the insulated cover glass system equipped with the external condenser without PCM (test 3), the uninsulated cover glass system equipped with the external condenser filled with PCM (test 2) and the simple solar still (test 1) have respectively the highest to the lowest yields. The system equipped with an external latent heat storage (test 4) demonstrates an increase of 86% in the yield compared with the simple solar still (test 1).

252 **Fig. 8** shows the variations in the temperature of different points and the amount of solar radiation for a system
 253 with external condenser filled with PCM for latent heat storage (test 4). As is observed, during the daytime, by
 254 an increase in the input solar radiation, the vapor (T_3) and saline water (T_1 & T_2) temperatures increase. By an
 255 increase in the vapor temperature (T_3 & T_4), the temperature of paraffin (T_5) also increases and the heat is
 256 stored as sensible at first. At 13:30, the vapor leaving the evacuated tube collectors (T_1) reaches the highest
 257 temperature of 97.3°C. From 13:30 onwards, paraffin temperature (T_5) reaches its melting point and the heat
 258 is stored as latent. The storage of latent heat continues almost until 17:30, and the temperature remains roughly
 259 constant in the meantime. From 17:30 to 21:00, the heat stored in paraffin is transferred to the saline water
 260 through heat pipes and makes it evaporate.

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 262 **Fig. 7** Cumulative water yield for different tests

263 The economic analysis of the present system was conducted by Dev et al [35]. In **Table 3**, the parameters
 264 necessary for the economic analysis for various tests are given. It is observed that the maximum and minimum
 265 CPL of 0.0266 \$/l/m² and 0.01378 \$/l/m² correspond to the tests 2 and 3 respectively.

Fig. 8 Temperatures of different points and solar intensity for a system with external condenser filled with PCM (test 4)

To perform a more accurate comparison of the tests, the daily efficiency of the systems are calculated from the following equation:

$$\eta_d = \frac{mL}{[\sum(IA) + p] \times t}$$

where η_d is the daily efficiency, m denotes the daily water yield measured in kg, L designates the latent heat of distillation measured in J/kg, I is the solar intensity measured in W/m^2 , A denotes the area of radiation absorber, p is the power of the fan measured in W, and t is the total time of the test.

In **Fig. 9**, CPL and daily efficiency for the different tests are given. Since the water yield of the tests 1 and 2 are low, they have a higher CPL as compared to tests 3 and 4. Minor increase of 1.43% in the efficiency of test 2 with respect to test 1 and addition of the costs associated with the storage system are responsible for the highness of the CPL of test 2 in comparison with that of test 1. In test 3, since the insulation of the glass has led to a 56% increase in the yield of the system, the CPL has considerably decreased as compared with tests 1 and 2. In test 4, although the cost of storage system is added to test 3, the CPL is just slightly higher than that of test 3, yet the yield has also increased and the daily efficiency has increased from 41.86% in test 3 to 50% in test 4. Therefore, among the tests conducted, test 4 is superior both from the CPL and efficiency perspective.

Table 4 presents a comparison between the daily efficiency of the present work with those of several other solar stills which have reported the daily efficiencies. It is observed that although the daily efficiency of the present work is higher than those of some other works, it is expected that by developing better designs for the PCM tank in the future, the rate of increase in thermal resistance resulted by PCM solidification could be reduced, and thereby, by enhancing the heat pipe performance, the night yield could be raised. In addition,

Table 3 Different parameters for economic analysis.

Parameters	Unit	Dev et al[35]	Test 1	Test 2	Test 3	Test 4
Principle cost (P)	\$	135.3	206	273	208	275
Salvage value (S) (10% of principle value)	\$	13.5	20.6	27.3	20.8	27.5
Life of the still (n)	Yrs.	20	20	20	20	20
interest rate (i)	%	10	10	10	10	10
Capital recovery factor CRF	-	0.117	0.117	0.117	0.117	0.117
Sink fund factor (SFF)	-	0.017	0.017	0.017	0.017	0.017
Annual first cost (CRF*P)	\$	15.9	24.102	31.941	24.336	32.175
Annual salvage value (SFF*S)	\$	0.24	0.3502	0.4641	0.3536	0.4675
Annual maintenance cost (0.15 annual first cost)	\$	2.38	3.6153	4.79115	3.6504	4.82625
Annual cost =(Annual first cost + annual maintenance cost - annual salvage value)	\$	18.04	27.3671	36.26805	27.6328	36.53375
Average daily yield	kg/m ²	4.1	3.5292	3.7292	5.495	6.555
Annual yield of the still (average daily yield *365)	kg/m ²	1496.5	1288.158	1361.158	2005.675	2392.575
Annual useful energy (annual yield*latent heat of vaporization (=0.65 kW h/kg))	kWh/m ²	972.7	837.3027	884.7527	1303.689	1555.174
Annual cost of distilled water per kg (annual first cost/annual yield)	\$	0.0106	0.01871	0.023466	0.012134	0.013448
Annual cost of distilled water per kWh (annual first cost/annual useful energy)	\$	0.0163	0.028785	0.036102	0.018667	0.020689
Cost per liter per unit area of still (CPL=Annual cost/Annual yield of still)	\$/l/m ²	0.0121	0.021245	0.026645	0.013777	0.01527

288 since the results are indicator of the higher performance of the system after the insulation of the glass, a smaller
289 basin for saline water can be manufactured and in addition to the cost reductions, vapor with higher temperature
290 can pass along the PCM and the yield could be raised by recycling larger amounts of energy.

Fig. 9 comparison of CPL and daily efficiency of different tests.

Table 4 Comparison of some solar stills in daily efficiencies.

Experiment	Solar system	Daily efficiency
Eltawil & Omara [36]	Developed solar still (DSS)	41
Eltawil & Omara [36]	DSS with hot water spray	38
Eltawil & Omara [36]	DSS with hot air	21
Eltawil & Omara [36]	DSS with spray and hot air	29
Omara et al [37]	Corrugated absorber, wick & reflectors	59
Omara et al [37]	Conventional still	33
El-Sebaï et al [23]	Sensible storage (sand)	37.8
El-Sebaï et al [23]	Conventional still	27
Omara et al [38]	Stepped still with internal reflectors	56
Omara et al [38]	Conventional still	34
Present study	PCM, Heat pipe & Evacuated tube collectors	50

307 **5. Conclusion**

308 In this study, a solar still equipped with an external latent heat storage system and evacuated tube collectors
309 was experimentally investigated. The storage system consists of paraffin as the phase change material and also
310 thermosiphon heat pipes as the devices which have the capability of unidirectionally conducting heat. The heat
311 released from the distillation process due to the condensation of vapor during the daytime makes the paraffin
312 melt and thereby heat is stored in the paraffin. In other words, the whole solar radiation is transferred to the
313 salty water and is not directly absorbed to the phase change material. The phase change material melts by the
314 passage of water vapor through it and stores the heat of distillation. In the evening, when the paraffin solidifies,
315 the latent heat released as a result of solidification is transferred to the saline water and enables the desalination
316 process to continue a few hours after sunset. The results revealed that by using phase change materials and
317 heat pipes to recover the latent heat of condensed vapor and storing it in the phase change materials, the
318 production continues a few hours at night resulting in an increase in the daily yield. Using an external condenser
319 without PCM and insulating the cover glass of the solar still jointly lead to the increase of 56% and the use of
320 an external condenser filled with PCM leads to an increase of 86% in the water yield. The maximum yield and
321 daily efficiency of 6.555 kg/m²/day and 50% were obtained for a solar still with an external condenser filled
322 with PCM. The economic analysis of the present system showed that the CPL of the yielded water in the best
323 case is 0.015 \$/l/m².

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