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Water solar distiller productivity enhancement using concentrating solar water heater and phase change material (PCM)

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ABSTRACT

This paper investigates usage of thermal energy storage extracted from concentrating solar heater for water distillation. Paraffin wax selected as a suitable phase change material, and it was used for storing thermal energy in two different insulated treasurers. The paraffin wax is receiving hot water from concentrating solar dish. This solar energy stored in PCM as latent heat energy. Solar energy stored in a day time with a large quantity, and some heat retrieved for later use. Water's temperature measured in a definite interval of time. Four cases were studied: using water as storage material with and without solar tracker. Also, PCM was as thermal storage material with and without solar tracker.The system working time was increased to about 5 h with sun tracker by concentrating dish and adding PCM to the system. The system concentrating efficiency, heating efficiency, and system productivity, has increased by about 64.07%, 112.87%, and 307.54%, respectively. The system working time increased to 3 h when PCM added without sun tracker. Also, the system concentrating efficiency increased by about 50.47%, and the system heating efficiency increased by about 41.63%. Moreover, the system productivity increased by about 180%.

1. Introduction

Human life sustainability depends mainly on water, together with the supply of energy [1]. Unfortunately, industrial Growth caused a deprivation of fresh portable water due to the ground contamination, as well as surface water streams. This obstacle resulted in the dispossession of the country growing in alarming phase. Distillation is carried out by several ways. Most of the existing distillation plants use fossil fuel as a source of energy [3]. All scientists agreed that the solar energy is one of the most acceptable alternatives for energy supply in many parts of the world [2]. Solar energy direct use is an admissible option that eliminates the major required operating cost. Solar distillation depicts a most simple and attractive technique compared to other distillation processes. It is suited to small and tiny units in areas where solar energy is widely abundant. Solar still design claims harmony of many factors like: brackish water depth, cohesive seal to prevent vapor leakage, cover slope, thermal insulation, shape and material of the still [4,5].

Abdullah [6] examined the solar still's yield using different types of absorbing materials. These materials were metallic

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wire sponges (coated and uncoated porous media) and black igneous rocks. The results showed that the highest water collection during day time could be achieved by the uncoated sponge. Followed by the black rocks and then coated metallic wire sponges. [7] demonstrated the transient mathematical models for an active single basin solar still with and without a sensible storage material at the lower part of the basin. Also, sand was used as a storage material. [8] studied the productivity of a double slope single basin, with basin area of 1.75 m^2.

Solar energy converted into different forms of energy, either to thermal energy or to electrical power. Solar energy converted into thermal energy by means of solar collector. Solar collectors have three types: flat plate collectors, evacuated tube collectors, and parabolic trough collectors [9].

Solar energy has an intermittent nature, as it is available only during the daytime. The sun intermittent nature considered as the main reason that hampers the reliability of solar energy as a primary source of energy [10]. The designed system must be able to supply energy at any time during the whole year. The solar energy systems can operate only for few hours during sunshine hours on summer days and much fewer hours during winter days. Therefore, lack of robust storage systems for solar energy is considered as the primary and most important problem that hampers the development and promotion of solar energy [11].

The storage of thermal energy by using the latent heat of the material is called latent heat storage. Latent heat defined as the amount of heat absorbed or released during the material phase change from one phase to another phase. There are two known types of latent heat which are latent heat of fusion and latent heat of vaporization [12]. In fact, latent thermal energy storage applications do not depend on latent heat of vaporization, due to the volume significant change accompanied by this type of phase change [13].

Phase change material storages are used to store energy in several practical application areas, and to balance temporary temperature alternations. In applications with a small temperature swing, PCM storage is preferable to sensible heat storage, because of its nearly isothermal storing mechanism and high storage density [14–16]. All materials are phase change materials. The phase change temperature is most important difference between these materials. Each material has its phase change at different temperature. In addition, each material has different values of latent heat and thermal conductivity [17,18]. The main drawback of most of the phase change materials is their low thermal conductivity that decreases the heat transfer rate. The phase change temperature adequate for the application temperature range is the most important feature for phase change material selection. Each PCM has its advantages and disadvantages, so one cannot mention a specific material that can be an ideal material used as an ultimate PCM [19].

Al-Hinti [20] conducted an experimental investigation of the performance of water-phase change material storage for use with a conventional solar water heating systems. Results showed that a significant difference between using water and PCM as a storage medium and using water only as a storage medium. Diaconu [21] investigated experimentally the determination of the enthalpy change and heat transfer characteristics of the new PCM. The study assessed the suitability of used PCM for integration into a low-temperature heat storage (cold storage) system for solar air conditioning applications. The results showed that the phase change intervals displayed higher values of natural heat transfer coefficient compared to water. It can rise to five times depending on temperature conditions. The optimum temperature range for heat storage overlapped on a temperature interval with high values of the natural convection heat transfer coefficient.

Tyagi [22] conducted an experimental work to determine the change in melting temperature and latent heat of fusion of calcium chloride hexahydrate inorganic salt as a latent heat storage material. The study used a thousand accelerated thermal cycle tests. A differential scanning calorimeter used to determine the thermal cycling effect and the reliability in terms of the changing of the melting temperature. Experimental results showed a good stability of thermal properties.

Eman-Bellah [23] carried out experiments to investigate a method to improve the thermal conductivity of paraffin wax by embedding aluminum powder in it. The size of the aluminum powder particles is 80 μm. Results showed that the value of the average heat transfer coefficient is greater for composite than for pure paraffin and charging time decreased by 60% for composite than that for pure paraffin wax. Useful heat gained increases with the addition of aluminum powder to the paraffin wax.

The aim of this paper is to investigate experimentally the enhancement and optimization of the distillation of conical distiller. A concentrating solar energy was used to increase storage energy and to offer sufficient period to allow the system to transfer heat to suitable phase change material. It is aimed to develop the still productivity.

2. Experimental setup

Fig. 1 represents the used rig in this study; it consists of the following three main parts:

2.1. Concentrator

The experimental setup consists of parabolic dish systems use a parabolic mirror that focuses incoming solar radiation on a receiver mounted above the dish at its focal point. This parabolic dish has 1.5 m diameter and 23 cm depth. Aluminum foils was adhered to the dish surface to make it work as a mirror. In front of the focal point, a heat exchanger was fixed. It fabricated from an aluminum container of 20 cm dia and 7 cm depth. This container isolated from outside by glass wool. Inside the container, a 1 m length tube of 0.96 cm dia was and immersed in paraffin wax (which acts as latent heat storage

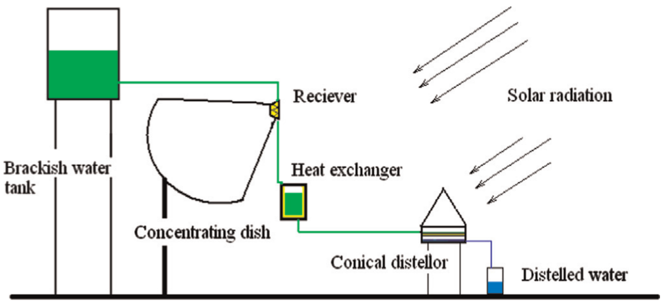

Fig. 1. A schematic diagram for the recent study rig.

Table 1
Thermo-physical properties for the used Iraqi paraffin wax in the present study.

Material property	Range
Melting temperature (°C)	45
Latent heat of fusion (kJ/kg)	190
Solid liquid density (kg/m^2)	930/830
Thermal conductivity (W/m °C)	0.21
Solid/liquid specific heat (kJ/kg °C)	2.1

material for the system) that fill the container from inside. The face of the container that encountered the dish consisted of two glass sheets of 2 mm thickness. Both covers fixed with rubber washers to prevent melting wax from leak to outside. The distance between the glass sheets was 1 cm. The container has two openings one in the top and the other one at the bottom. The wrapped tube connected from these openings with two plastic pipes linked this pipe with another heat exchanger. Concentrator was turned to face the sun manually every half an hour.

The used paraffin wax was chosen due to the followings desirable properties:

i. Low boiling point
ii. High specific heat
iii. High latent heat
iv. Non-corrosiveness for most of the fabrication materials
v. Wide useful range
vi. Easily available in the market and low in cost
vii. Excellent stability in the working range
viii. Low freezing temperature
ix. Should not form scales in the tubes

Table 1 lists the thermo-physical properties of the used paraffin wax in the recent study. All these properties were tested and measured at Chemical Eng. Dept. Laboratories, UOT, Baghdad.

2.2. Heat exchanger

Inside this heat exchanger, heat was exchanged between distilled water inside the wrapped pipe coming from the dish and brackish water inside this barrel. This barrel was located lower than the focus point heat exchanger and higher than the distiller basin to allow hot water flow by thermal siphon wheel. This barrel fabricated with a circular shape and had dimensions of 0.5 m dia and 0.5 heights. It manufactured from plates and consisted of two drums, between these two drums 2 cm gap which was filled with wax. This barrel isolated from outside thoroughly with glass wool.

2.3. Conical distiller

In recent study, a manufactured conical type solar still was used. It made from fabricated plate with a circular area of the diameter of 70 cm. The hot brackish water in the heat exchanger barrel was supplied to the conical water distiller which consisted significant base with a float to adjust hot water entrance to the distiller. The water controlled by 1 cm height. Polyethylene pipes were used to transport the hot water to solar still basin from the water treasurer. A wax layer of 1 cm thickness placed under the base of the distiller to preserve the water temperature at night. A plastic conical cover fixed to the base with 70 cm height; this cover represented the condenser for the steam produced from the lower base. The condensed distilled water collected at the bottom of this cover by means of two small channels. These channels were welded to collect the slipping distilled water from the transparency lid. These channels extended longitudinal on two sides with 5° inclination from the horizon. Distilled water was gathered in a plastic container and measured. The still base was isolated from its basis with a glass wool layer to prevent heat exchange with outdoor. A plastic stuffing used to ensure the steam complete blockage and to prevent its leakage to outside the stiller,. This stuffing was of 1 cm width and 3 mm thickness. This substance was fixed by silicon material to confirm total adherence of the plastic stuffing on the upper edge. A non-shiny selective black color was used to paint the inner surface of the metal basin, to increase solar absorption. The still was kept in the sunlight.

3. Measurements

Varied temperature measurements conducted by means of thermocouples type K. Four thermocouples were fixed on the condenser surface to assure complete distribution of temperatures for all the transparency cover area. Two thermocouples attached to the outer surface and two on the inner surface. The average cover temperature obtained from the mean of these thermocouples readings. A single thermocouple was fastened in the distiller basin bed to measure its temperature. Two thermocouples were used to measure wax temperatures inside the distiller. The treasurer brackish water temperature measured by a mercury thermometer; it fixed in the connecting pipe. Four thermocouples were distributed in the heat exchanger treasure wax to pursue its phase changing process. Two thermocouples used for the concentrator wax and one for concentrator hot water measurements. The environment temperature measured by a thermometer placed in the shadow. The measured temperatures recorded at regular intervals of time (every hour starting at sunrise). These thermocouples were calibrated using a calibrated mercury thermometer in the laboratory. The gathered distilled water volume measured by means of a cylindrical vessel of 5 l capacity. The collected water measured every hour starting at the beginning of a new day.

The data of incident radiation received from Iraqi meteorological organization-Baghdad. The mathematical formula to determine the focal point distance (exchange place):

$$x^2 = 4fy \tag{1}$$

x – Solar concentrator radius.
y – Solar concentrator depth.
f – Focal point distance.

It must be mentioned that the concentrator was not fixed in the focal point exactly, but it was made slightly forward from it. The focal point is a point as it name manifests, while the concentrator has an area, and this area must be covered with solar radiation.

$$\text{The Incident solar energy} = I \times A_{\text{concentrator}I} \tag{2}$$

I – Solar radiation intensity.
A – Concentrator area.

The concentrator reflectively made 70% due to aluminum foil, while the dish surface reflected radiation efficiency to concentrator made 90%. The heat exchanger material absurdity made 65%.

$$Q_{\text{concentrator}} = m_w c_{pw} \Delta T_w + m_{\text{wax,con}} c_{p,\text{wax,con}} \Delta T_{\text{wax,con}} \tag{3}$$

$$Q_{\text{distillator}} = \dot{m}_w c_{pw} \Delta T_w + m_{\text{wax,dist}} c_{p,\text{wax,dist}} \Delta T_{\text{wax,dist}} \tag{4}$$

$$\eta_{\text{concentrator}} = \frac{Q_{\text{concentrator}}}{I \times A_{\text{dish}}} \tag{5}$$

$$\eta_{\text{distillator}} = \frac{P \times h_{fg}}{I \times A_{\text{distillator}}} \tag{6}$$

Where: h_{fg} – distiller basin water latent heat,
P – Productivity (l/m^2),
$A_{\text{dist.}}$ – Distiller basin area.

4. Procedure

Hot water is generated by solar concentrator; this hot water heats paraffin wax, hence, its temperature increases. The heat exchanger water will transfer a part of the thermal energy by convection, and conduction will transfer the other part of energy to the PCM in the treasure. Hot brackish water will heat the basin liner temperature, and when it becomes higher than that of the PCM, heat will transfers from basin liner to PCM causing increments in its temperature. Sensible heat first stored till the PCM reaches its melting point. As the PCM melts it saves energy as latent heat. After PCM completes melting, the heat will be stored as a sensible heat, again.

At afternoon, the solar radiation decreases and the still components temperatures start to reduce. Heat begins to transfer from the liquid PCM to water through the basin liner until the PCM completely solidifies. In this period, the PCM will act as a heat source for the basin water. Consequently, the still continues to produce distilled fresh water after sunset depending on the PCM layers in the rig components.

The tests conducted for four cases:

Case I: without using paraffin wax and without sun tracking.

Case II: without using paraffin wax and with sun tracking.

Case III: with using paraffin wax and without sun tracking.

Case IV: with using paraffin wax and with sun tracking.

Tests conducted in Baghdad City – Iraq springtime weathers. It was carried out starting from 15-February and ended on 30 April. In order to constrict the expenditures, one dish, and two stills used. This procedure requires conducting the tests in individual days. Every week four shiny and bright days (relatively similar in wind speed) were taken for measuring system variables. Measuring time began at 7 AM till distilled water temperature returned to its starting temperature.

5. Results and discussion

Fig. 2(a)–(c) represent the temperatures variation with time for the four studied cases for each element of the system. Fig. 2(a) shows water temperature variation ($T2$) at the concentrator with time. When the dish was not tracking the sun, the resulted temperatures always were less than tracking cases. Also, using PCM material expanded the working hours of the concentrator due to the energy it stored. PCM addition to concentrator made it operate 3.6% for case 3 compared with case 1 while it expanded its operation by about 16.89% for case 4 compared with case 3.

The resulted heat exchanger temperatures (T_3) were depending on concentrator temperatures. It took the same style of the former figure as Fig. 2(b) declines. Using a wax with sun tracking (case 4) gave the maximum temperatures of the time

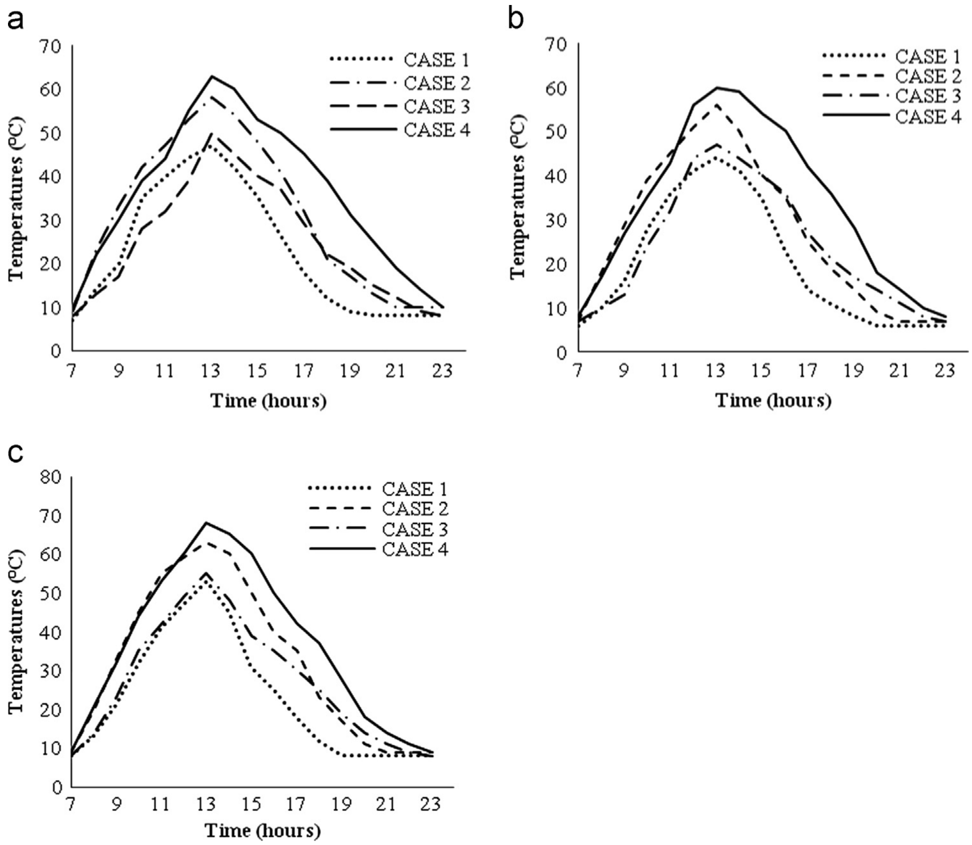

Fig. 2. (a) $T2$ variation with time for the four studied cases. (b) $T3$ variation with time for the four studied cases. (c) T4 variation with time for the four studied cases.

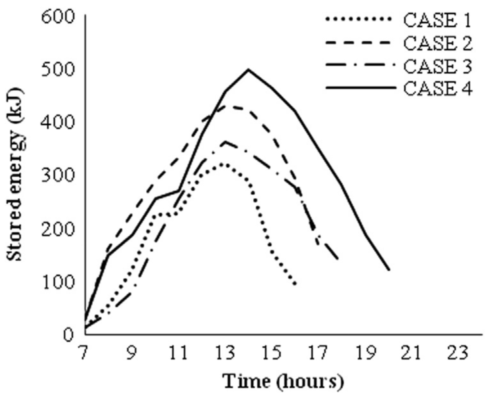

Fig. 3. Stored energy in the dish component variation with time for the four studied cases.

especially for the period after 2 PM. Also, the figure shows that case 3 advanced in case 2 for the period from 4 PM till sunshine due to wax existence. The increments in temperature for the whole day hours was 35.9% for case 2 compared with case 1, and 40.54% for case 4 compared to case 3.

Although the water flowed from the heat exchanger to distiller with high temperature, distilled water temperatures (T_4) increased more due to its exposure to sunlight as Fig. 2**(c)** demonstrates. Increasing distilled water temperature is crucial as it is related to water vaporization. From the other hand increasing distilled water temperature for high levels may increase the condenser walls (conical distiller) temperature which means reducing distilled water condensation. Condenser elevated temperature depends mainly on the surrounding air temperature. The tests conducted in springtime of 2014 where air temperatures were temperate and suitable to increase productivity.

Comparing the concentrator stored energy with time gives preference to case 4 as Fig. 3 shows. Using paraffin wax as PCM in the concentrator increased the concentrator working hours and the energy it stored. The increments in stored energy were 73%, 38.6% and 124.1% of cases 2, 3 and 4 respectively compared with case 1. The increment in concentrator energy means increasing distiller working time, which is the PCM main job, and it took it over successfully.

Fig. 4 shows the distiller stored energy variation with time for the studied cases. It supposed that all the energy enters to distiller used in evaporating the water, but in this study there are many stored energies due to using PCM. PCM in the distiller gave two advantages; first stored energy and secondly prevent the temperature oscillation especially after 12 AM. The increments recorded for energy stored in distiller were 54.91%, 31.68% and 94.47% of cases 2, 3 and 4 respectively compared with case 1. It must notice that the increment in energy stored for the PCM added cases (case 2 and 4) gave the highest rank.

Increasing stored energy and incident solar energy increased the distiller productivity indeed, but there are many other factors the productivity depends on. The condenser and evaporator temperatures variation are one of these factors. In this study, the tests were conducted in the same weather conditions (in shiny days) to prevent any variation that may cause an error or uncertainty in the results. Also, this procedure ensures that the primary reason for any variation was the PCM addition. The addition increased the productivity highly as Fig. 5 records. Productivity increments were 180%, 53.21% and 307.54% of cases 2, 3 and 4 compared with case 1 respectively. These results were agreeable with stored energy results, which mean that adding PCM to distiller system increases its productivity in high levels.

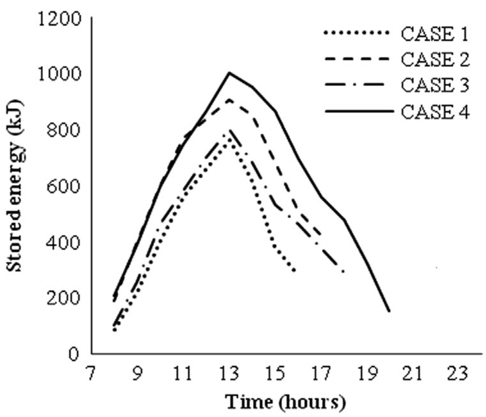

Fig. 4. Stored energy in the distiller variation with time for the four studied cases.

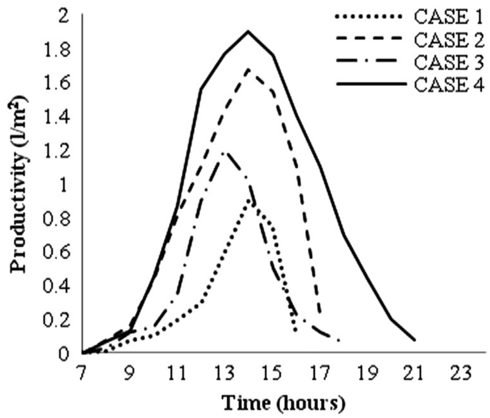

Fig. 5. Distiller productivity variation with time for the four studied cases.

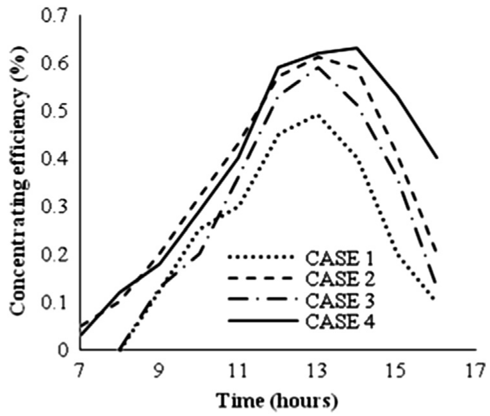

Fig. 6. System concentrating efficiency variation with time for the four studied cases.

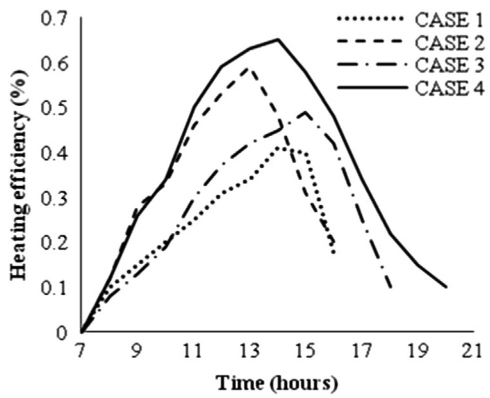

Fig. 7. System heating efficiency variation with time for the four studied cases.

Concentrating efficiency improved with tracking the sun, and with adding PCM also, as Fig. 6 declines. Tracing the sun means gathering more solar rays, results in more thermal energy stored. While adding PCM to the system means improving energy storage in high levels. Curves in Fig. 8 illustrate that adding PCM to the system is more efficient than tracking the sun. Also, using both methods together increased concentrating efficiency highly. The concentrating efficiency increments were 50.47%, 21.64% and 64.07% for cases 2, 3 and 4 respectively compared with case 1.

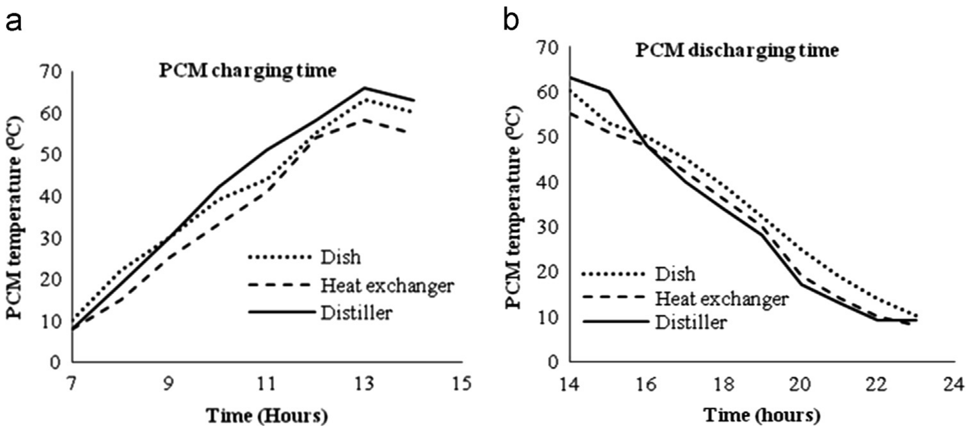

Fig. 8. (a) PCM charging temperatures variation with time for the three PCM locations. (b) PCM discharging temperatures variation with time for the three PCM locations.

Adding PCM to the system improved its heat storage and the time of system working as Fig. 7 represents. Heating water system discontinued heating water with the sunset. While PCM system continued heating water after sunset taking advantages of heat stored in phase changing process. The increments in heating efficiency were 41.63%, 37.33% and 112.87% of cases 2, 3 and 4 respectively compared to case 1. PCM added to the system still more efficient in improving heating efficiency than heating water by tracking the sun only.

Fig. 8(a) and (b) represent the charging and discharging time for paraffin wax through all operation time of the system. Charging time starts from the beginning of the day until 1–2 PM, as Fig. 8(a) shows. In this period, dish PCM warmed by concentrated sun radiation reflected from the dish wall, and wax temperature equal to water temperature in focal drum. Heat exchanger PCM charged by hot water coming from dish set, that is why its temperatures always retarded from dish temperatures. Distiller PCM takes its heat from two sources, first hot water coming from the heat exchanger, secondly from sun rays. That is why its wax temperatures exceeded other waxes temperatures especially for the period from 10 AM to 2 PM. The figure results indicate that paraffin wax reached its melting point around 11 AM, but it continued warming to surpass melting point temperatures with several degrees. PCM temperatures settle down at melting point until all wax is being melted, after that PCM temperature return to increase. Temperature constancy at melting point did not exceed 15 min (this is the change phase time), after that it starts clamping to higher degrees (this is the sensible heat stored in PCM).

PCM temperatures in the three locations reduced in discharging period (Fig. 8(b)). The maximum reduction appears in the distilled temperature due to its exposure to cold air. Heat exchanger PCM temperatures decreased more than dish PCM due to cold brackish water movement. This significant reduction in temperature started at 4 PM. The PCMs in all locations reached phase change period at 5 PM, this period lasted about 25 min. After this time, PCM started to warm water with its stored sensible heat.

6. Conclusions

Tests conducted on a concentrating distillation system consist of concentrating dish, heat exchanger, and conical distiller. Tests perfumed at Baghdad, Iraqi springtime, 2013. The major findings of this study are:

1. Tracking the sun by concentrating dish caused (case 2):
a. Increased water temperatures in the distiller with about 50.47%.
b. Increased system concentrating efficiency to about 41.63%.
c. Increased system heating efficiency of about 37.33%.
d. Increased system productivity by about 180%.

2. Adding PCM to heating water system with a solar concentrator caused (case2):
a. Increased system working time with about 3 h.
b. Improved system concentrating efficiency to about 21.64%.
c. Increased system heating efficiency of about 36.33%.
d. Increased system productivity by about 53.21%.

3. Tracking the sun by concentrating dish with adding PCM to heating water system caused (case 4):
a. Increased system working time with about 5 h.
b. Improved system concentrating efficiency to about 64.07%.
c. Increased system heating efficiency of about 112.87%.

d. Increased system productivity with by 307.54%.

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