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Design and assessment of solar concentrator distillating system using phase change materials (PCM) suitable for desertic weathers

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ABSTRACT

A desertic region always suffers from a lack of fresh water in a large portion of its area. In these areas, available water from swamps or ground water wells is brackish water, and it must be purified or distillated. In this paper, we introduce a simple distillation system accompanied with a concentrating unit. This system was assembled and installed with very low costs. Also, paraffin wax was used in this study as phase change materials to absorb heat from the heated water. The concentrating system, which consists of a dish accompanied by a drum as a storage device and pipes assembly fixed at dish focal, was used to heat brackish water. The conical distiller was fabricated to contain PCM under its base to increase the stored energy. Tests were conducted at Baghdad, Iraqi wintertime 2013–2014. The study declares that this system is suitable to desert weathers with acceptable productivity compared with other existing systems. Adding PCM to the concentrating distillation system increased system working hours, increased concentrating efficiency with about 50.47%, increased system heating efficiency with about 157.8%, and increased system productivity with about 783%. Comparing this study with other Iraqi studies and those in literature gave convincing agreement. This study contains valuable information for researchers, industrials, and investors interested in solar water desalination system investment in Iraq and desertic weather countries.

Keywords: Latent Heat storage capacity; Phase change materials; Paraffin wax; Conical distiller; Solar concentrating

1. Introduction

Solar thermal energy is considered as the most available renewable source of energy and it is available in direct and indirect forms [1]. Iraq, which lies in the highest solar intensity region in the world, has numerous hours of sunshine as shown in Table 1. The studies showed that Iraq has about more than 3,000 radiance hours per year in Baghdad and even more in other places (south governorates). The hourly solar intensity varied between 316 W/m^2 in January to 833 W/m^2 in June [2]. Table 2 represents the monthly average solar intensity that reached Baghdad station for the period from 1983 to 2012.

The usage of the latent heat of the material to store thermal energy is called latent heat storage [3]. All materials are phase change materials [4]. The main

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Table 1
The monthly rate of theoretical and practical solar brightness at Baghdad environmental station (h/d) for the period (1983–2012) (IMO, 2013) [17]

Month	Theoretical brightness (h)	Actual brightness (h)
January	10.15	6.4
February	11.1	7.5
March	11.55	8.1
April	13.2	8.8
May	13.59	10.2
June	14.30	13
July	14.1	12.8
August	13.29	12.2
September	12.22	10.7
October	11.19	9.1
November	10.18	7.5
December	9.58	6.1

Table 2
Monthly rate of arrived solar intensity at Baghdad environmental station ($W/m^2/d$) for the period (1983–2012) (IMO, 2013) [17]

Jan	Feb	March	April	May	June	July	August	Sep	Oct	Nov	Dec	Average
333.1	348.2	469.1	541.4	726.8	732.4	731.6	861.2	560	435.4	289.1	245.1	506.36

drawback of the most of phase change materials is their low thermal conductivity that decreases the heat transfer rate [5,6]. Paraffin wax is used in this study as phase change material. Paraffin wax is one of the organic heat storage phase change material (PCM) for commercial applications; it consists of straight chain hydrocarbons having melting temperatures ranging between 23 and 67˚C [7]. Paraffin waxes have the following advantages: Kinds of paraffin are available in a large temperature range; it has no tendencies to super cool, and it is chemically stable. Also, it shows high heats of fusion; it does not segregate, and finally paraffin waxes are safe and non-corrosive [8]. Iraq paraffin wax is selected for this study because of its low prices that don't exceed 2 $/kg in local markets.

Human life sustainability depends mainly on water resources along with the supply of energy. The access to fresh water is a fundamental need of all societies [9]. Fossil fuels drive most of the desalination plants, and renewable energy derives only 0.02%. A simple, inexpensive desalination system that operates by renewable energies becomes a sustainable need [10,11]. Direct solar desalination method is used for small production systems, such as solar stills. These distillers are suited for regions where the fresh water demand is about 200 m^3/d [12].

The purpose of using a concentrator system is to improve the performance of solar still. Solar radiation is concentrated through the concentrating unit, and it increases the thermal energy transferred to the basin water modifying its evaporation. The generated vapor rises and condensates on the interior side of the glass cover [13]. Many researchers proved that using a concentrating system accompanied with solar distiller improved basin water temperatures and increased its fresh water production. Rabl et al. [14] studied the effect of maximum concentration of several parabolic concentrators. El-Kassaby et al. [15] studied a distillation system using a parabolic reflector concentrator line type that is used for sea water distillation. Ortega et al. studied the concentrator as vapor generator for solar-ammonia and water absorption refrigerator [16].

Although Iraq has two great rivers (Tigris and Euphrates) supplying the main part of fresh water needs, still a large part of Iraq is suffering from lack of fresh water or brackish water availability that needs distillation. Most distillation projects are old or out of order that increases these places' sufferance.

The aim of this study is to design, implement, and assess a new design concept that consists of a simple concentrating solar thermal storage distillation system. The proposed system integrates with using PCM. This system is characterized by its high productivity and cheap price. This simple system is implemented from available and low prices materials. This system was experimentally investigated to evaluate its productivity and efficiency in Iraqi wintertime where the solar intensity is at a lower level.

2. Experimental setup

The used rig in this study consists of the following two main parts:

2.1. A- Concentrating unit

This system consists of a dish assembly which uses a parabolic reflector that focuses incoming solar radiation on a container mounted above the dish at an advanced point from its focal. This parabolic dish has 1.5 m diameter and 23 cm depth. The inner surface of the dish is covered by an aluminum foil to make it work as a reflector. The receiver is fixed in an advanced place to the focal point to confirm receiving all dish reflected rays. The receiver is fabricated from an aluminum container of 20 cm diameter and 7 cm depth. The receiver shadow subjected on the collector's face can decrease the amount of solar radiation reflected, so the receiver's insulation thickness is limited. A glass wool 1 cm thickness is used to isolate the container from its back. A 1 m copper tube of 0.96 cm diameter was rounded and immersed in paraffin wax (acted as latent heat storage material for the system) that fills the container from inside. A glass cover of 2 mm thickness was used to cover the side facing the dish. The cover was fixed with a rubber washer to prevent melting wax from leaking to the outside. The container has two openings, one in the bottom of water interring the container from the brackish water container, and the other from the top for hot water exit to the distiller. The parabolic dish tilt angle was chosen at 30° from the horizon facing the south, depending on conclusions of reference [18]. The concentrating system costs did not exceed 120 US$ and all the materials used are available in Iraqi markets.

It must be declared that it is very difficult to implement a parabolic dish without a two-axis tracking system. The recent study setting, fixed angle from the horizon facing south works only for flat non-focusing type collectors. Also, a trough type concentrator has been used at a stretch with some design tweaks and reduced concentration ratio. A fixed dish concentrator only works for a short period during the day, where the rest of the day focus/reflection reduced. In this study, a novel design idea was to take advantage from the high solar intensity of Iraq at concentrating hours that was from 11 AM to 2 PM. So, although the concentrating time is limited, the PCM latent storage enhanced the system productivity as the results indicate. However, the focusing system works effectively on direct solar irradiation, which required taking into consideration another loss. The main part of diffused radiation that is about 20% of the solar beam cannot be focused. For this reason, flat collectors are used for low-temperature applications (diffuse radiation is not lost). The setting procedure employed in this study limited the lost diffuse radiation.

2.2. A- Distiller system

Conical-type solar was still used in this work (Fig. 1). A fabricated plate was used for the basin of the solar still, with a circular base area of the diameter of 70 cm. The basin inner surface is colored with non-shiny selective black color to increase solar radiation absorption. The still is kept in the sunlight. The brackish water is supplied to the conical water distiller from the concentrating unit. The water is maintained at 1 cm height using a height float in the basin. The water flowed into the solar still basin through polyethylene pipes connected to the heat exchanger inside the concentrating system. The flow of brackish water is not continuous and steady, and the formed vapor can stop it. This point was taken into consideration, and an aperture in the brackish water storage tank for ventilation was left opened. A paraffin wax layer of 1 cm thickness is placed below the base of the distiller to preserve the water temperature after sunset. The still base was isolated from its basis with a glass wool layer to prevent heat exchanging with outdoor. Table 3 lists the used paraffin wax thermophysical properties. All these properties were tested and at Chemical Engineering Department Laboratories, UOT, Baghdad.

A plastic conical cover was fixed above the base with 70 cm height. This cover represents the condenser for the steam produced from the lower base. The condensed distilled water was collected at the bottom of this cover in a plastic container which was fixed below the distiller assembly. Distilled water was gathered in a plastic container and measured every operating hour. The transparency cover was adhered to the plastic basin container to prevent water leakage outside the distiller. Fig. 2 represents a photographic picture for the rig used in the study.

The contribution in the recent design seeks to improve the existing mainstream technologies:

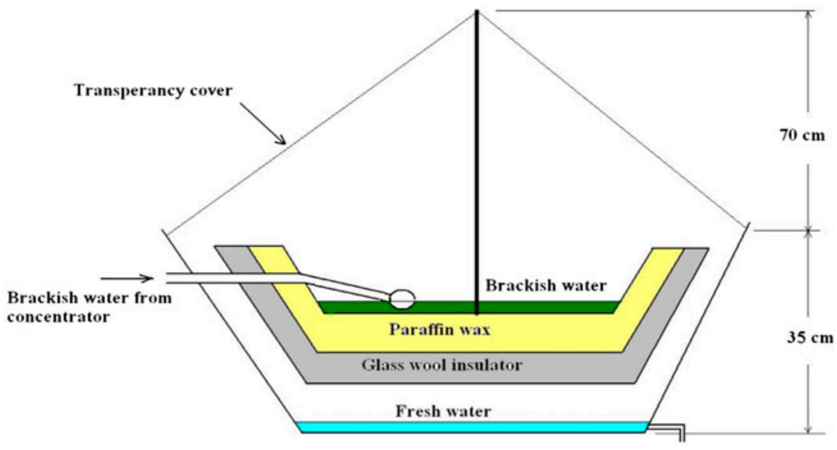

Fig. 1. A schematic diagram for the conical distiller.

Table 3
Thermophysical 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 specific heat ($c_{p_{w_s}}$) (J/kg°C)	2.384
Liquid specific heat $c_{p_{w_l}}$ (kJ/kg°C)	2.49

(1) Flat thermal collectors with distillation [19].
(2) Photovoltaic energy harvesting coupled with osmosis desalination unit [20,21].
(3) Solar pond coupled with distillation unit [11,22].

3. Measurements

Several thermocouples type K were used to measure various temperatures. These thermocouples were calibrated in the laboratory. Two thermocouples were fixed on the condenser surface. One thermocouple was fixed on the outer surface and the second on the inner surface. The average of these thermocouple readings was taken to represent the average cover temperature. Another thermocouple was fixed in the distiller basin's bed to measure its temperature. Two thermocouples were used to measure wax temperatures inside the distiller. The temperature of the water from the concentrating unit to the distiller was measured using another thermocouple fixed in the connecting pipe. The concentrator's wax temperatures were measured by using two thermocouples. A thermometer was placed in the shadow used to measure the surrounding temperature. The measured temperatures were noted at regular intervals of time (every hour starting at sunrise).

The distilled water quantities were measured utilizing 5 L capacity vessel. The gathered water was measured every hour starting from 7 AM. The collected purified water amount was left out and recorded at the end of each hour.

The data of incident radiation was obtained from the Meteorological Department of Baghdad.

$$\text{The Incident solar energy} = I\,A_{\text{concentrator}} \tag{1}$$

The focal length is crucial to determine the focus center that leads to the determination of the receiver position. The focal length was calculated by:

$$\text{Focal length } (f) = \frac{1}{4 \cdot a} \tag{2}$$

where

$$a = \frac{\text{Depth}}{\text{radius}^2} \tag{3}$$

Concentration ratio is a very useful parameter that helps to get an estimation of the receiver working temperatures. In the same time, this ratio gives a good indication of the thermal efficiency of the system. The concentration ratios are determined by Eqs. (5–7) [23].

$$A_r = \frac{\pi}{4} d^2 \tag{4}$$

From the definition of the geometric concentration ratio, it excludes the concavity of the concentrator in

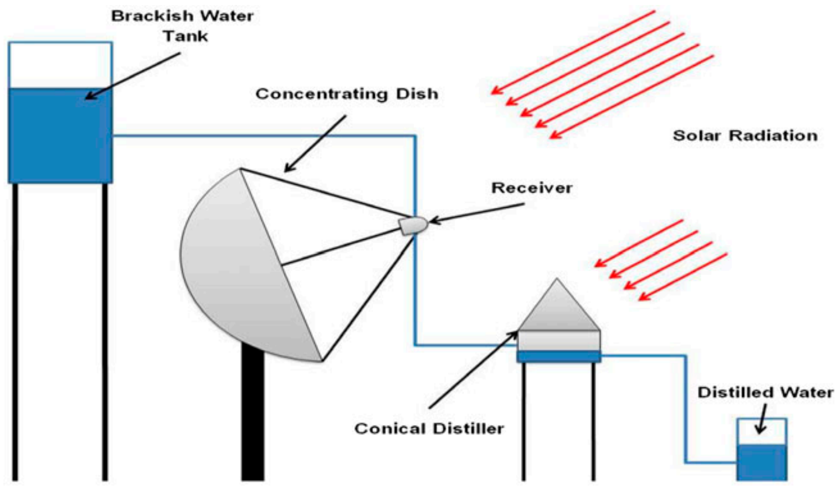

Fig. 2. A schematic diagram for the recent study rig.

the calculation of the concentrator area. The concentrator's concavity causes an increase in the surface area, but the solar radiation intensity is per unit area of the face of the earth, not the concentrator's surface.

$$A_c = \frac{\pi}{4} D^2 \tag{5}$$

where

$$\text{Geometric concentration ratio} = \frac{A_c}{A_r} \tag{6}$$

The useful stored energy which was collected from the concentrating system can be calculated by equation [24].

$$Q_{\text{stored}} = m_w \, c_{p_w} \Delta T_w + m_{\text{wax}_{\text{con.}}} \, c_{p_{\text{wax}_{\text{con.}}}} \, \Delta T_{\text{wax}_{\text{con.}}} \tag{7}$$

The thermal efficiency of the solar concentrating system can be obtained by equation [24].

$$\eta_{\text{hourly}} = \frac{Q_{\text{stored}}}{\rho_m \cdot I \cdot A_{ac}} \tag{8}$$

$$A_{ac} = A_c - A_{ro} \tag{9}$$

The total heat loss from the receiver can be assumed by calculating conduction heat loss ($Q_{l.k}$), convection heat loss ($Q_{l.c}$), and radiation heat loss ($Q_{l.r}$):

$$Q_l = Q_{l.k} + Q_{l.c} + Q_{l.r} \tag{10}$$

The major losses from the cavity receiver come from the convection and radiation heat losses. The amount of heat loss by the conduction from the insulated receiver is normally too small compared with others (radiation and convection heat loss). Therefore, in this paper the conduction heat loss is assumed [25,26]

$$Q_{l.k} = 0$$

The equation gives the convection heat loss [28]:

$$Q_{l.c} = h_c \times A_{ro} \times (T_{ro} - T_a) \tag{11}$$

Convection coefficient heat transfer due to the wind velocity can be calculated by equation [28]:

$$h_c = 16.9 \times V^{0.45} \tag{12}$$

where V is the wind velocity (m/s) obtained from the Meteorological Department of Baghdad.

Radiation losses from the receiver are given by equation [28]:

$$Q_{l.r} = \epsilon \times \sigma \times A_{ro} \times (T_{ro}^4 - T_{\text{sky}}^4) \tag{13}$$

σ: The Stefan-Boltzmann constant (5.667×10^{-8}) $[W/(m^2\,K^4)]$.

$$T_{\text{sky}} = 0.055 \times T_a^{1.5} \tag{14}$$

There are two outside parts of the receiver surface with two different surface temperatures. The inner surface was covered with aluminum foil and outer back side surface was covered with glass wool insulation:

$$Q_l = (Q_{l.r} + Q_{l.c})_1 + (Q_{l.r} + Q_{l.c})_2 \tag{15}$$

where insulation covers the receiver outside emissivity-coefficient is $\epsilon = 0.04$.

The stored heat in the distiller was calculated by Eq. [3]:

$$Q_{\text{distillator}} = m_w\, c_{p_w} \Delta T_w + m_{\text{wax}}[c_{p_{w_s}}(T_m - T_i) + \Delta h + c_{p_{w_l}}(T_f - T_m)] \tag{16}$$

The equation calculates the distiller efficiency [19]:

$$\eta_{\text{distillation}} = \frac{P \times h_{fg}}{I \times A_{\text{distillator}}} \tag{17}$$

4. Test procedure

This system takes advantage of solar energy in two places. First: the reflected radiation from the concentrator that heats paraffin wax as well as the brackish water inside the copper pipe immersed in wax. Secondly, the warm water coming from the concentrator settles in the distiller basin and exposes the solar radiation traversing through transparency cover. The water temperature increases and evaporation process results. Besides, the hot water increases the heat gained by the wax under the basin. When the solar radiation ceases, the liquid wax inside the concentrator container transfers heat to the brackish water through a heat exchanger. The still base PCM functioned in same way as the wax in the dish container. The heat transfers from liquid PCM to the basin liner and water after the still components start to cool down. This operation continues until the PCM solidification process is completed. In this procedure, it is guaranteed that the PCM heats the basin water during low solar intensity periods as well as during the night. At the same time, a continuous production of fresh water after sunset depending on the PCM layers in the rig components is ensured.

The tests were conducted at Iraqi wintertime weathers (December 2013 and January 2014). Each month the system was operated, and measures were taken eight times for each studied cases, and the average was calculated and plotted against working hours. Table 4 lists the studied cases dates, time, and wind velocities. The dish was fixed facing south to gather more radiant. The investigated three cases were:

Case 1: without a concentrating system (The conical distiller alone).

Case 2: with a concentrating system but without using paraffin wax.

Case 3: with a concentrating system and using paraffin wax.

The three cases performance comparison was made by using one system on three successive days. This procedure was used to confirm that the environmental conditions for the three cases were similar.

5. Results and discussions

Fig. 3 represents the distribution of the average solar intensity variation with daytime for the studied period. These solar intensity values are provided from the Iraq Meteorology Organization for each hour of the tested period. The figure shows that solar intensities of Iraq at winter time are higher compared with data from most countries in Europe. The high solar intensity of Baghdad city and Iraq, in general, is the indication of the importance of this energy that is still, unfortunately, not used.

Fig. 4 demonstrates that using conical distiller alone (case 1) increased the water temperature at a lower level compared with using concentrator to heat brackish water in the second instance. Increasing distillated water temperatures for high levels increases the condenser walls (conical distiller) temperature, which means reducing distilled water condensation. The reduction of condenser wall temperature depends mainly on the surrounding air temperature. The tests were conducted in December 2013 and January 2014 where the air temperatures were low and suitable for productivity increment. PCM was used in case 3 to store solar energy, so in the morning (compared to the system without PCM (case 2)) part of the heat which was absorbed by the brackish water transferred to PCM. As a result, case 3 temperatures in this interval were relatively lower compared with case 2. In the afternoon, water temperatures declined quickly causing productivity reduction in cases 1 and 2, while water of case 3 stayed preserving heat that allowed it to produce more portable water. The distiller water temperature increased by about 37.17 and 94.38% for cases 2 and 3, respectively, compared with case 1 temperature for one-day operation.

Fig. 5 shows a comparison of the system which stored energy with time. PCM existence gives preference results. Using PCM with the concentrator increased, the working hours of the system and the energy were stored due to its high latent heat. PCM existence in the distiller gave two advantages; first storing energy and secondly preventing the

Table 4
List of the studied cases

Case studying	Month	Date	Average wind velocity (m/s)
Case 1	December 2013	2/12/2013	0.4
		9/12/2013	0.58
		16/12/2013	0.32
		23/12/2013	1
	January 2014	6/1/2014	1.04
		13/1/2014	1.03
		20/1/2014	0.97
		27/1/2014	0.99
Case 2	December 2013	3/12/2013	0.44
		10/12/2013	0.45
		17/12/2013	0.48
		24/12/2013	0.47
	January 2014	7/1/ 2014	1.13
		14/1/2014	1.1
		21/1/2014	.99
		28/1/2014	1.07
Case 3	December 2013	4/12/2013	0.43
		11/12/2013	0.5
		18/12/2013	0.47
		25/12/2013	0.48
	January 2014	8/1/2014	1.27
		15/1/2014	1.2
		22/1/2014	1.16
		29/1/2014	1.1

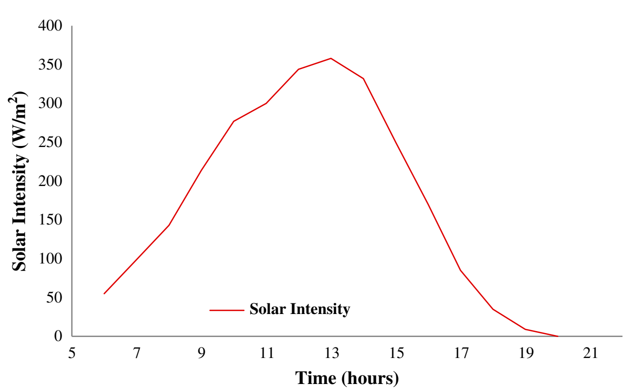

Fig. 3. Average solar intensity versus time for the studied period of Baghdad city.

temperature oscillation at sunset. The increment in stored energy was 226.4 and 466% for cases 2 and 3, respectively, compared with case 1.

Fig. 6 records increment in system productivity with the concentrating system addition to the conical distiller and another increment due to PCM addition to the distillation system at afternoon in case 3. The concentrating system addition increased the productivity highly by about 350 and 428.5% for cases 2 and

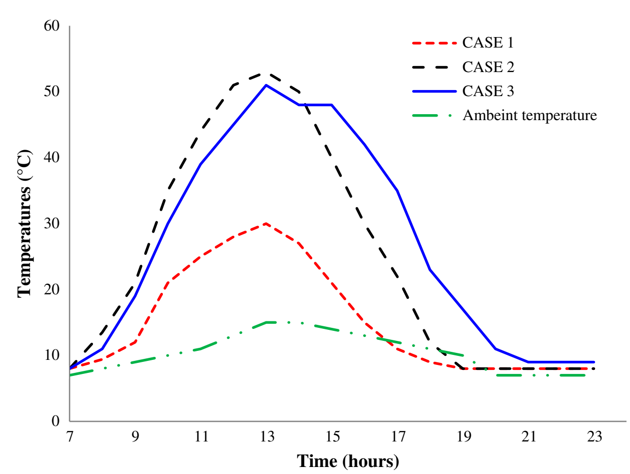

Fig. 4. Water temperatures in the conical distiller for the studied cases.

3, respectively, compared with case 1. The system production stopped for cases 1 and 2 after sunset in few minutes, while the system in case 3 continued producing fresh water due to PCM thermal storage abilities. This result indicates the real productivity for the studied simple and cheaply designed system.

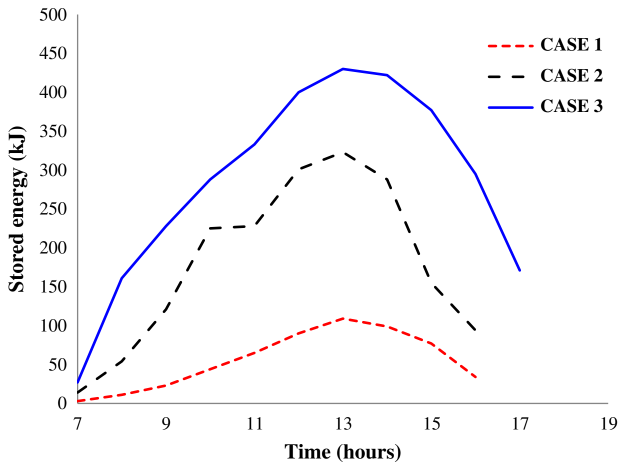

Fig. 5. Stored energy in the conical distiller for the studied cases.

Fig. 7 represents that adding concentrator system and PCM to the conical distiller improved its hourly thermal storage efficiency and the time of system working. Adding PCM to the system (case 3) is more efficient in improving heating efficiency than (case 2). At morning period, although case 3 water temperatures were less than case 2 as Fig. 4 declares, the hourly storage efficiency of case 3 preceded that for case 2. The thermal heat stored in PCM caused this antecedence.

Fig. 8 represents the phase changing period for the paraffin wax from solid to liquid phases vs. time. The temperature remained constant during phase changing period. The figure declares that temperature increments varied slightly between the wax in the concentrator and that existed in the distiller. The concentrator wax temperature was higher than that of the distiller wax because the dish received sun radiation and concentrated it causing high temperatures. While the distiller got its heat from two sources: water coming from the concentrator and the sun radiation, the evaporation process inside the distiller reduced its temperature. The liquefaction time for the concentrator's wax happened before that of the distiller wax and ended before it also.

Fig. 9 clarifies the wax phase undergoes conversion period from the liquid state to the solid state versus time. The evaporation process inside the distiller caused a reduction in still wax temperatures. This reduction was lower than the quicker solidification process of wax in the dish container. The concentrator gained its heat from concentrating the sun radiation that stopped with the sunset, while it continued losing its storage heat for supplying hot water to the distiller. The distiller made use of this heated water to reduce the heat taken out from its wax. In spite of all this, the solidification process for both wax parts happened in a converging time.

Fig. 10 manifests a comparison between the recent study and other similar Iraqi experimental works. The distiller water basin temperature was employed for the comparison between these studies. Ahmed [19] used preheating brackish water using solar flat plate water heater. Salman [29] used reflection mirrors to concentrate sunlight on the distiller. Both studies were selected due to the same working period in Iraq wintertime weathers. The recent survey shows converging results with other works with higher water temperatures at the afternoon period compared with the others due to PCM usage.

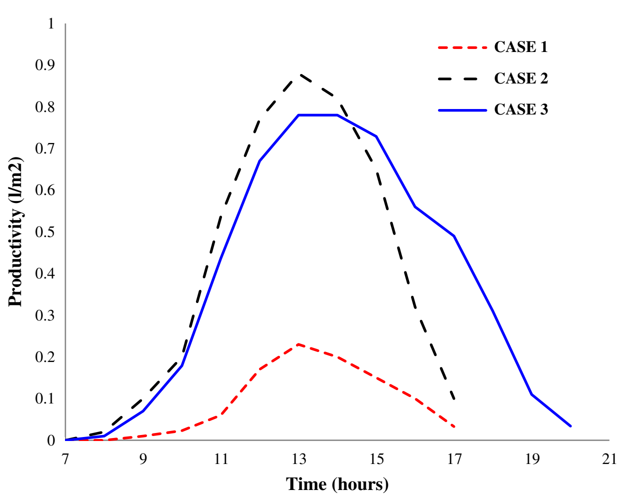

Fig. 6. System productivity for the studied cases.

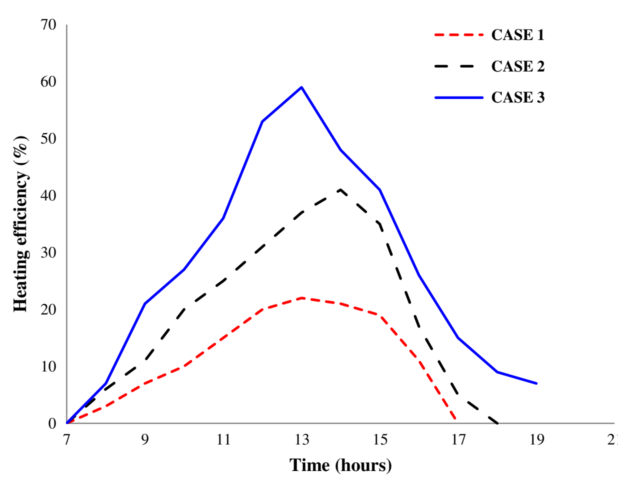

Fig. 7. System hourly efficiency for the studied cases.

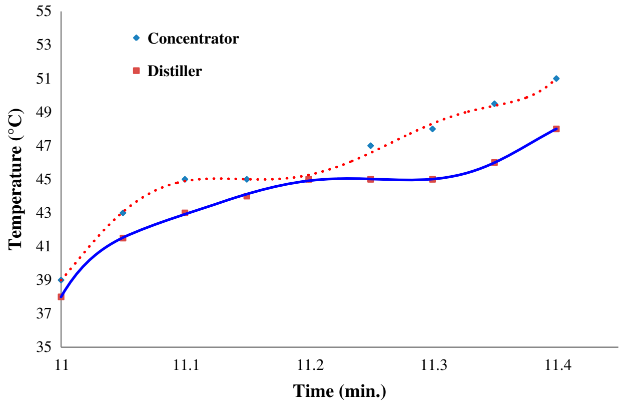

Fig. 8. Paraffin wax phase changing (solid/liquid) behavior vs. time.

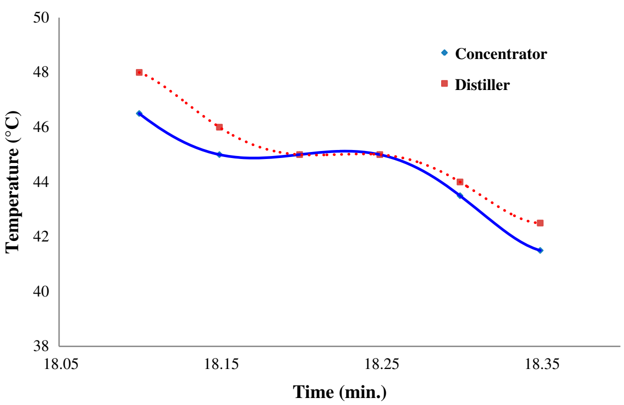

Fig. 9. Paraffin wax phase changing (liquid/solid) behavior vs. time.

Fig. 11 declares a comparison between the recent study and other international experimental works using PCM with their distillation systems. The distiller productivity was applied as a comparison factor of these studies. The selections of the comparison studies depended on the period of the year when each study was conducted (wintertime for all studies). Also, they all used different phase change materials in their investigations. Also, their distiller's areas were close. Swetha [30] examined a single-slope single-basin solar still with adding (Lauric acid) as a PCM layer under the liner of the basin. Ria [31] used (Zinc Nitrate Hexahydrate) as a PCM added to double-slope single-basin solar still reservoir. Gowtham [9] tested desalination system using concentrating solar thermal energy through a parabolic trough concentrator with paraffin wax added to the distiller. The recent study gives the highest productivity compared with other studies.

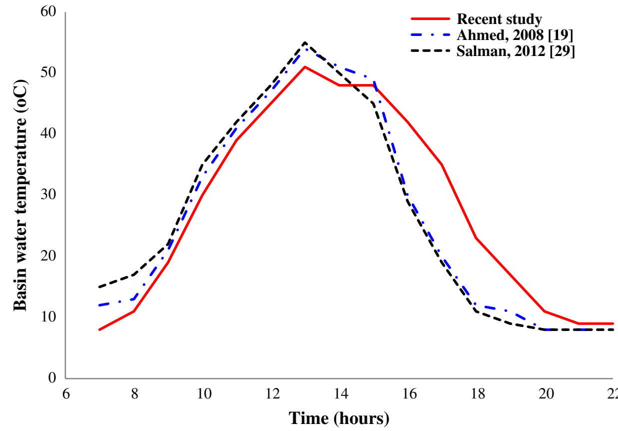

Fig. 10. Comparison with other experimental Iraqi research.

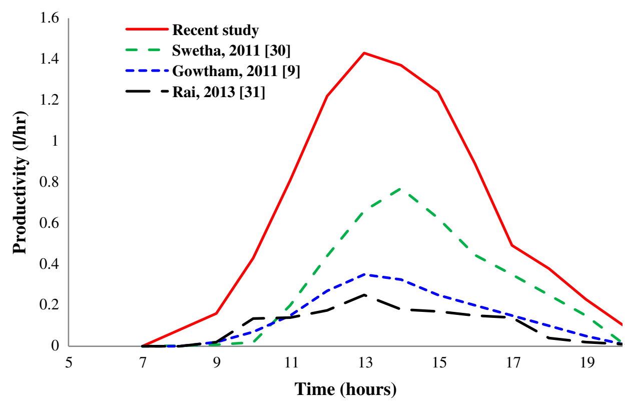

Fig. 11. Comparison with other experimental international research.

The recent study shows productivity superiority due to two main reasons: first, the study was conducted in Iraq weathers characterized with higher solar intensity compared with other studies. Secondly, the concentrating system used in the recent survey with PCM addition to its structure was more efficient compared with other studies. It is worth mentioning here that Swetha and Rai did not use concentrators, while Gowtham used parabolic trough without adding PCM to the concentrator unit.

6. Conclusions

Tests performed on a concentrating distillation system consisted of concentrating dish and conical distiller. The tests were conducted at Baghdad, Iraqi wintertime 2013–2014. The main findings of this study are:

(1) Adding the concentrating system supplied with PCM to distiller caused:

    (a) Increasing water temperatures in the system with about 94.38%.
    (b) Increasing system heating efficiency with about 157.8%.
    (c) Increasing system productivity with about 428.5%.

(2) Although the paraffin wax is cheap in Iraq markets because it is produced from oil, its addition to distillation system showed a significant enhancement in the system productivity and thermal storage.
(3) Using this system gives high distilled producing rates and enables solving the fresh water lack in Iraqi villages, country areas, and deserts.
(4) This system is fabricated from cheap, available materials, and it is uncomplicated that it can be collected and installed by any unqualified person.
(5) A comparison with other similar Iraqi experimental studies showed good agreement. The recent survey demonstrates progressive improvement compared with some international studies, depending on Iraqi high solar intensity and the better-concentrating system used in the study.

Nomenclature

A_{ac}	—	effective area of the collector (m^2)
$A_{\text{Concentrator}}$	—	interior surface area of solar dish concentrator (m^2)
A_c	—	aperture of concentrator area (m^2)
A_{dist}	—	the distiller basin area (m^2)
A_r	—	aperture of receiver area (m^2)
A_{ro}	—	area of receiver with insulation cover (m^2)
C_p	—	specific heat at a constant pressure for water = 4,200 (kJ/kg K)
$c_{p_{w_s}}$	—	specific heat of wax at solid state (kJ/kg K)
$c_{p_{w_l}}$	—	specific heat of wax at liquid state (kJ/kg K)
f	—	focal length (m)
h_c	—	convection coefficient heat transfer (kJ/kg)
h_{fg}	—	the distiller basin water latent heat (kJ/kg)
Δh	—	wax latent heat of fusion (kJ/kg)
I	—	solar radiation intensity for every hour of the day (W/m^2)
m	—	mass (kg)
m_{wax}	—	mass of wax (kg)
P	—	productivity (l/m^2)
Q_l	—	the total heat loss from the receiver
$Q_{l.k}$	—	the conduction heat loss
$Q_{l.c}$	—	the convection heat loss
$Q_{l.r}$	—	the radiation heat loss
$(Q_{l.r}+Q_{l.c})_1$	—	surface of aluminum foil covers heat losses
$(Q_{l.r}+Q_{l.c})_2$	—	outside insulation surface of the container heat loss
Q_{stored}	—	stored energy
V	—	the wind velocity (m/s)
T_m	—	wax melting temperature (°C)
T_i	—	wax temperature at solid state (°C)
T_f	—	wax temperature at liquid state (°C)
Greek letters		
ρ_m	—	reflectivity value for aluminum foil materials = 0.78 (Günther, 2011)
σ	—	the Stefan-Boltzmann constant = (5.667×10^{-8}) (W/m^2 K^4)
ϵ	—	aluminum foil emissivity-coefficient = 0.9
η_{hourly}	—	the hourly thermal efficiency of the solar concentrating system (%)

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