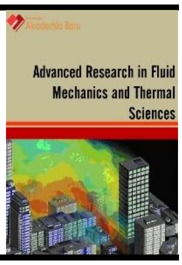
Penerbit Akademia Baru

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences

Journal homepage: www.akademiabaru.com/arfmts.html
ISSN: 2289-7879



Thermal Performance of Different Solar Distillators Under Iraq Climate Condition

Open Access

Areej Hamza Hilal[1,*], Karima E. Amori[1]

[1] Department of Mechanical Engineering, College of Engineering, University of Baghdad, Iraq

ARTICLE INFO

Article history:
Received 11 August 2019
Received in revised form 10 September 2019
Accepted 13 September 2019
Available online 15 December 2019

ABSTRACT

In this work, a novel single-slope solar distillator of floating perforated absorber inserted with wicks (cotton ribbons), and a stepped distillator are designed and manufactured with the aim of developing the conventional distillator. They are examined experimentally at Baghdad, Iraq (33.3°N Latitude, 44.4°E Longitude) in order to enhance the freshwater productivity and the efficiency of the conventional distillator. Results showed that the daily productivity and efficiency of the stepped distillator are higher than that for conventional solar distillator by 30% and 36.19% respectively. The daily productivity and thermal efficiency for the distillator with the floating absorber are higher than that for the conventional distillator by 16% and 26% respectively. Daily productivity and the efficiency of the stepped distillator are higher than that for the distillator with floating absorber by 11.8 % and 32.9 % respectively. It has been concluded that the stepped distillator is higher productivity and efficiency than the conventional distilled and the distillator with the floating absorber.

Keywords:
Desalination; conventional distillatory; stepped distillatory; wick; perforated absorber; thermal efficiency

1. Introduction

Many areas in central and southern Iraq suffer from water salinity and lack of fresh water. Solar distillation can bring fresh drinking water from saltwater and from available, cheap and uncontaminated energy (solar energy). The people's need for freshwater and the increase in fuel prices encouraged the rapid development of solar energy. One method of desalination is solar distillation, which is a thermal application of solar energy. Its principle is to evaporate water using the energy of solar irradiance then condense water vapor to fall in the form of freshwater drops.

In the past two decades, research has increased in the design and study of new types of solar distillators to improve their efficiency and increase productivity. The improvements include various forms of solar distillators as well as various additives. More researches have been carried out to improve the productivity of solar distillates based on multiple variables that have a part in improving the efficiency of the system [1], which is ranging from 2.5 to 5 l/m^2d, either by purifying groundwater

* *Corresponding author.*
E-mail address: areejhamza1@gmail.com (Areej Hamza Hilal)

or desalinating saline water [2]. In order to enhance the productivity of the stepped solar still, it was modified to reduce the area of the basin by the use of small trays by Ali *et al.,* [3]. Fins, Internal and external reflectors, and external condenser were used to increase condensation and evaporation processes within the solar still. The results showed a significant increase in productivity where it is increased from 6.9 to 8.9 kg /m^2. A theoretical study was conducted to compare between the different types of phase change materials (PCMs) and their effect on the productivity of solar still by Kabeel *et al.,* [4].

An economic study was conducted on specific types of PCMs to select the best PCM to increase the productivity of solar still at a low cost. The results show that the inorganic PCM capric-palmitic and organic PCM A48 have high productivity characteristics and low cost. It was also found that the thickness of PCM does not affect the productivity so prefer to use thin layers of it to reduce the cost. A radiation model was developed to show the effect of solar distillation walls on the amount of solar radiation falling on the saline water and the basin [5]. The capabilities of this model were compared with previous models. The results showed that increasing the length of the walls has the opposite effect on the efficiency of solar still. It was found that the best length of the front wall of the solar still is less than about 0.10 meters. Also, it is reported that increasing the length of the still reduces the shadow of the side walls and thus increases the efficiency of the distillator. Designed and tested a copper inclined stepped solar still with water depth (3 cm) under a wet tropical climate is carried out by Mohammed *et al.,* [6].

A high performance copper inclined stepped solar still is resulted due to the high thermal conductivity of copper. The productivity of this still increases with the increase in the intensity of solar radiation and the ambient temperature, where the productivity reached about 4383 mL/m^{2}d. It was observed that the productivity of the stepped solar still increases with ambient of low humidity. A wick layer in the basin is used to increase the evaporation area and thus increase distillator productivity. The distillator is also tested with the aluminum rectangular fin which covered with different wicks. It is found that the highest productivity was for a light black cotton cloth for a wick type distillator. The aluminum rectangular fin covered with cotton cloth was more effective than the light black cotton cloth [7]. The production of desalinated water by consuming solar power, and produced and distributed the electric power-driven by the solar power plant are studied. Analytical results showed that larger desalination plants and solar power plants were more efficient than smaller plants [8]. Double basin solar still is studied experimentally to pick out the optimum water depth and define the cost of freshwater production. The daily solar distillation output was (11.064 kg) for a water depth of (30 cm). The cost of freshwater per kilograms was about 0.37 Rs/kg by the double basin solar still [9].

A modified Fresnel solar collector system is used to study experimentally seawater thermal desalination. Results showed that the modified Fresnel solar collector system produces high thermal energy and can be attributed to their relatively high optical efficiency and low thermal loss [10]. The conventional single slope distillator is developed to improve its performance, by inserted a reticular porous layer in the basin of distillator. It is showed that the modified solar still produced 17.35% higher distilled water in comparison to conventional distillatory [11]. The quantum of water production for distillator is improved by using phase change material (Paraffin wax) that stored thermal energy. The distillator is coupled with a Fresnel lens to concentrated solar radiation on the absorber plate by increasing received thermal energy. It is found that the maximum hourly still productivity was achieved between 12:00 and 14:00, the accumulated productivity at the end of the day was (6.3 liters) [12]. Inclined trays are used in copper-stepped solar still to increase the efficiency of the system. The consequences showed that the inclined copper-stepped solar still has a daily efficiency ranging between 28% and 29% from Sep. to Dec. 2016 [13].

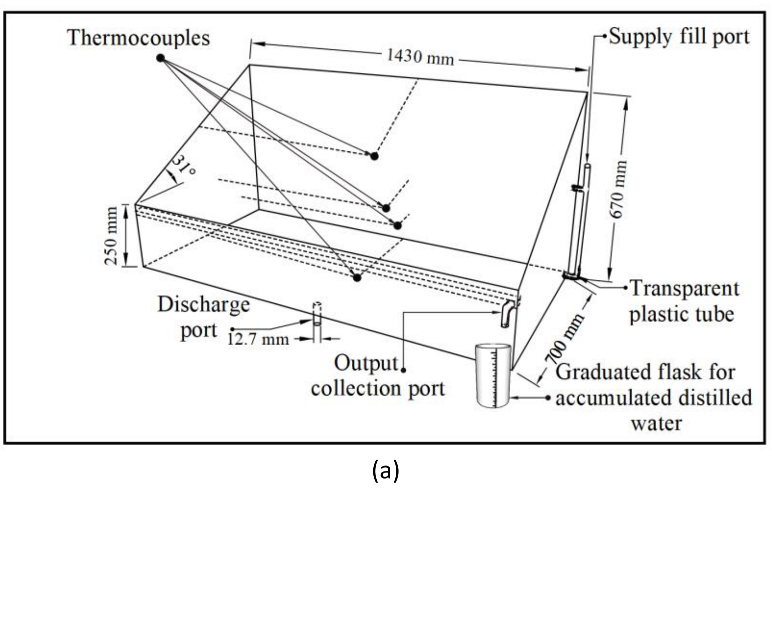
An experimental study to improve the performance of a simple single-slope solar distillator by a change in the design of the conventional solar distillator for an increase in condensation process without the use of any condensation [14]. The results showed the possibility of improving the productivity of the conventional distillator by increasing the size of the distillator relative to the basin and this is a clear increase in the condensation area as well as additional heating of water inside the distillation basin using reflective plates. The performance of stepped solar still united to photovoltaic thermal (PV/T) collector studied experimentally and numerically. The effect of design and operation conditions on freshwater productivity, energy efficiency, and output electrical power are involved [15]. Results showed a great agreement between the modeling data with the experimental data. The energy efficiency increases by about more than twice and freshwater productivity increases by about 20%.

The objectives of this work are to investigate experimentally the productivity and thermal efficiency of different designs for solar distillators. Therefore, a side by side the distillator with a floating absorber, conventional, and stepped solar distillators are tested under Baghdad-Iraq climate conditions (Lat. 33.3° N, Long. 44.4° E) to specify their productivity and efficiency. The novelty of this work is based on modified the conventional distillator by design and manufacturing a distillator with floating absorber and stepped distillator. For the manufacture of distillator with a floating absorber, a wick material (made from cotton ribbons) inserted in the pores of the copper absorber plate. For the manufacture of stepped distillator, a copper absorber plate is formed into ten steps with two basins welded inside the distillator. Per the authors' knowledge, no previous similar work is reported.

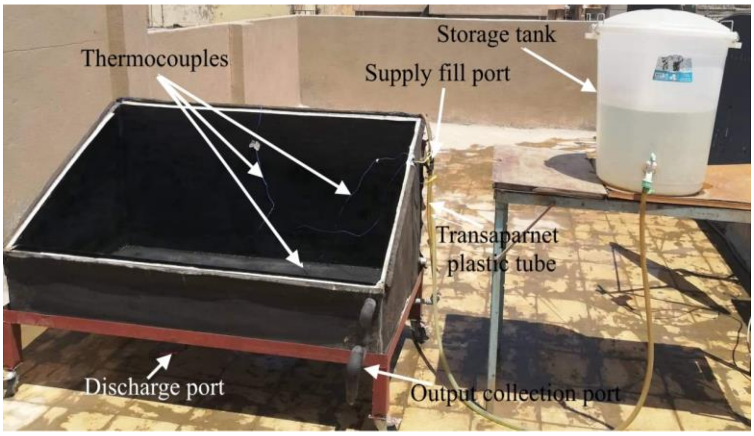
2. Experimental Setup

2.1 Conventional Distillator

Figure 1(a) and 1(b) illustrates a schematic layout and photograph of the conventional single slope basin solar distillator. This setup is comprised of a basin, glass cover, insulation, and piping. The basin area is 1 m^2 and a height of 250 mm from the front and 670 mm from the back of the basin that forms a 31° tilted angle of the glass cover (close to the latitude of Baghdad city (latitude 33.3° N) to achieve the highest received solar energy [16]). The glass cover thickness is 4 mm. The distillator is fabricated from galvanized iron 1.6 mm thickness. The inner surface of the distillator was painted with mat black dye. The lower free edge of the body of the basin is welded with a slightly inclined channel, made of U-shaped galvanized iron sheet of (height 30 mm and width 30 mm) to collect the distillate water.



(a)



(b)

Fig. 1. (a) Schematic diagram of conventional solar distillatory and (b) photograph of the distillator

Geometrical and thermophysical properties of the distillators are given in Table 1. Armaflex (AF) thermal insulation layer was used of (25 mm) thickness for insulating the basin from the bottom and sides. Saline water is supplied to the basin from a plastic storage tank of (50 Litter) capacity to keep a constant water level in the basin.

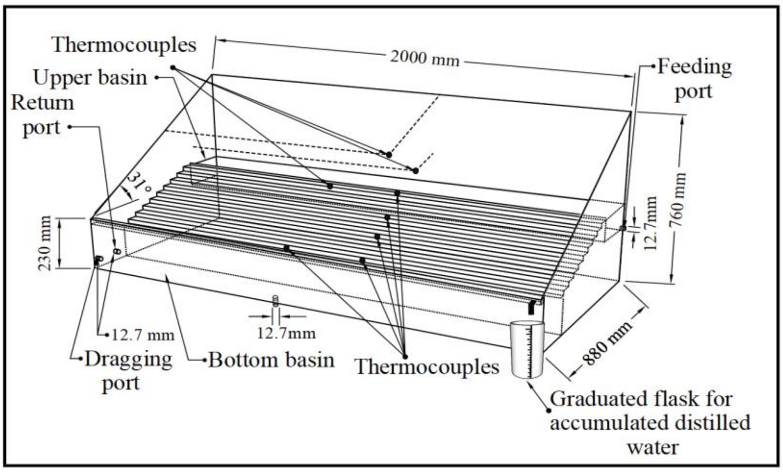
Table 1
Properties of different parameters for conventional and stepped distillators

No.	Name	Item	Geometrical properties		Thermophysical Properties [17]			Physical properties		
			area (m^2)	mass (kg)	density ρ (kg/m)	k (W/m.K)	C (J/kg.K)	α [18]	τ [15]	ε [17]
1	Conventional distillator	Glass cover	1.17	18	2700	1.05	800	0.05	0.95	0.95
		Saline water	1	30	997	0.163	4179	0.05	0.95	0.96
		Absorber plate	1	12.6	7870	80.2	447	0.89	-	0.28
2	Stepped distillator	Glass cover	1.12	18.4	2700	1.05	800	0.05	0.95	0.95
		Saline water	1.32	6.6	997	0.163	4179	0.05	0.95	0.96
		Absorber plate	0.96	11.8	8920	401	384	0.9	-	0.03
3	Floating distillator	Glass cover	1.17	18	2700	1.05	800	0.05	0.95	0.95
		Saline water	1	30	997	0.163	4179	0.05	0.95	0.96
		Absorber plate	0.96	11.8	8920	401	384	0.9	-	0.03

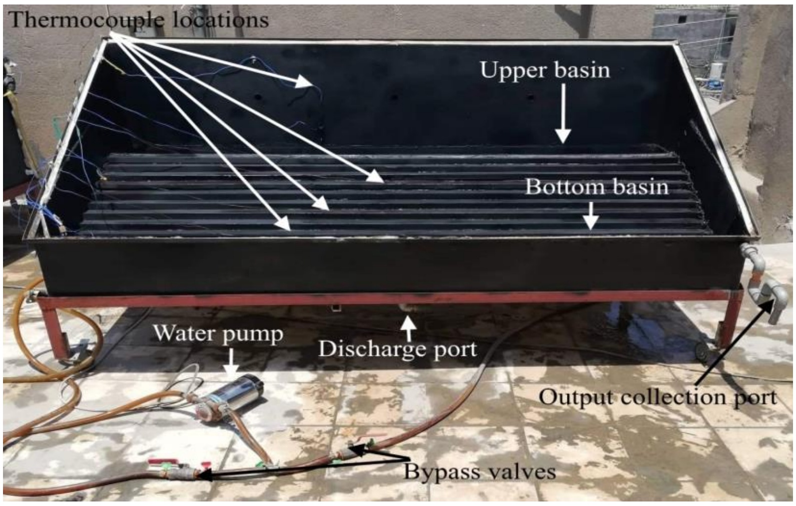
2.2 Stepped Distillator

Figure 2(a) and 2(b) shows the stepped solar distillator that consists of two basins, absorber plate, glass cover, insulation, water pump, and piping. Two basins from galvanized iron 1.6 mm thickness, of 0.4 m^2 were constructed and welded into distillator. The first basin is welded to the rear wall of the distillator, (upper side) to feed water to the stepped absorbing plate. The second basin is welded to the distillator lower side to collect saline waterfall then it is recirculated to the upper basin. The two covered basins were welded inside the distillator to prevent leakage to or from the distillator. The stepped distillator area was 1 m^2. A copper absorber plate of (1 mm) thickness and (2 m * 0.66 m) area is formed into ten steps of dimensions (2 m length, 0.05 m width, and 0.02 m height) to work as an absorber.

Journal of Advanced Research in Fluid Mechanics and Thermal Sciences
Volume 64, Issue 1 (2019) 92-106



(a)



(b)

Fig. 2. (a) Schematic Diagram of Stepped solar distillatory and (b) Photograph of the distillator

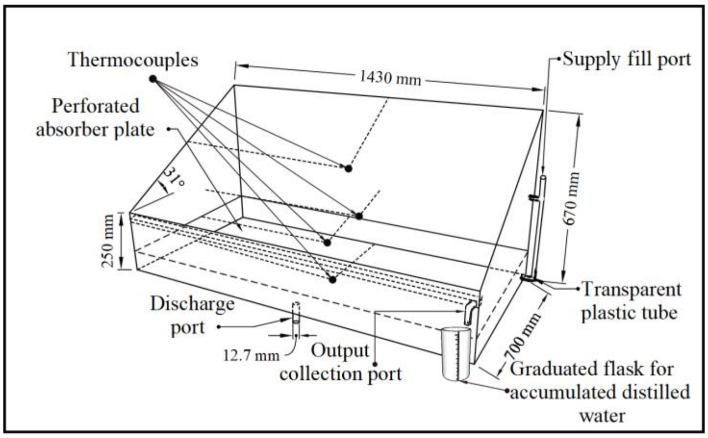
2.3 Distillator with a Floating Absorber

This distillator is shown in Figure 3(a) and 3(b) which is symmetrical to the conventional basin. The distillator absorber copper plate of (660 x 1330 mm) is perforated with 96 slots of (2 x 20 mm) dimensions. Wicks (made from Cotton Ribbon) of dimensions (2 x 20 x 250) mm, shown in Figure 4(a) are inserted in the slots of the absorber as shown in Figure 4(b). These wicks are used to absorb water from the basin of the distillator to the absorber surface. The inner surface of the distillator and the perforated plate are black painted. Armaflex (AF) thermal insulation layer was used of (25 mm) thickness for insulating the basin from the bottom and sides. Saline water is constantly supplied to the basin from a plastic storage tank of (50 liters) capacity to keep a constant water level in the basin.

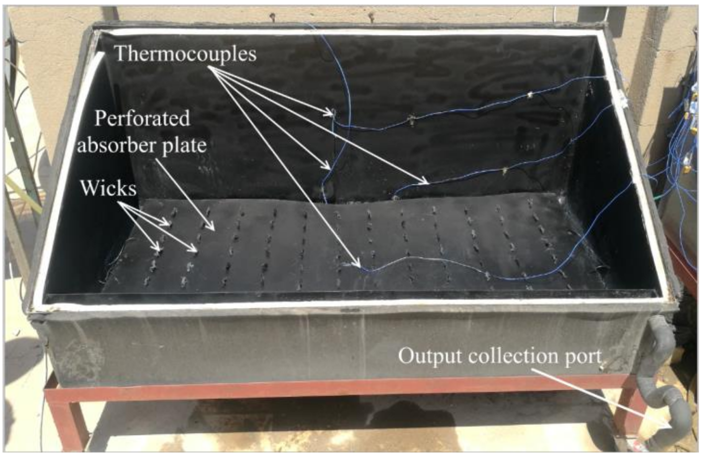
Twelve calibrated thermocouples (type-K) connected to a Digital data logger temperature recorder with SD card data logger model BTM-4208SD are used. The calibration data are given in Table 2. The sensors are used to measure: basin, absorber plate, water, vapor, and glass cover temperatures as shown in Figure 1, Figure 2, and Figure 3. The accumulated distilled water is measured by 2 liters graduated glass flask. Ambient temperature, wind velocity, solar radiation, and climate condition were obtained from the environmental center belongs to the Ministry of Sciences and Technology for Baghdad, Iraq.

Table 2
Thermocouple's calibration data

Indicator Reading (°C)	0	10	20	30	40	50	60	70	80	90	100	110	120
Thermocouple Reading (°C)	0	10	19.5	30	39.7	50	60	69.3	79.8	90	99.7	109.7	111.7

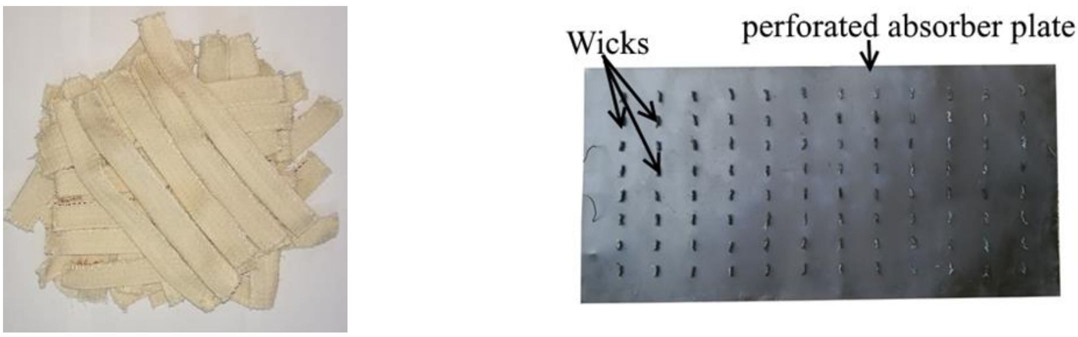


(a)



(b)

Fig. 3. (a) Schematic diagram of solar distillator with floating absorber and (b) photograph of the distillator



(a) (b)

Fig. 4. (a) Wicks (Cotton ribbons) and (b) absorber plate with wicks

2.4 Experimental Procedure

A side by side test on the distillator with a floating absorber, conventional and stepped distillators were held in Baghdad/ Iraq, (33.3° N Latitude, 44.4° E Longitude) for sunny clear days, from 8 am to 5 pm. The effect of different designs of the three distillators on the productivity and the efficiency of the distillators were investigated. The distillator with a floating absorber performance was tested at a water level of 30 mm and (5 mm) heights of prominent parts of the wicks (cotton ribbons) over absorber plate. The performance of distillators was tested at a water level of 30 mm, and a flow rate of 3 l/min for conventional and stepped distillators respectively. The solar radiation, ambient, absorber plate, water, water-vapor and glass cover temperatures were recorded every 10 min. Distilled water yield is hourly monitored from 8:00 to 17:00 then it is measured at 8:00 am next day.

2.5 Uncertainty

The accuracy of obtaining experimental results depends on the accuracy of measurement instrumentations and the repeated observation analysis of repeated tests. The range, accuracy and percentage error for the instruments used are given in Table 3. The uncertainty analysis of this study is estimated based on Holman Method [19].

Table 3
Accuracies and error for various measuring instruments

No.	Instrument	Accuracy	Range	% error
1	Thermocouple (°C)	± 0.1	0– 100	1
2	Solar Radiation (W/m^2)	± 10	0 – 5000	2
3	Length (m)	0.0005	0 -1	0.05
4	Graduated flask (ml)	± 1	0 – 2000	0.5

3. Data Processing
3.1 Solar Radiation

The measured solar radiation on a horizontal surface was converted to solar radiation on a tilted surface Duffie and Beckman [20]

$$G_{T,total} = R * G_{total} \tag{1}$$

where
G_{total} is total (beam and diffuse) solar radiation on a horizontal surface (W/m^2).
$G_{T,total}$ is total (beam and diffuse) solar radiation on the tilted surface (W/m^2).
R is the ratio of solar radiation on the tilted surface to that on a horizontal surface at any time, it is calculated as

$$R = \frac{Cos\ \theta}{Cos\ \theta_z} \tag{2}$$

where θ is incidence angle, which is the angle between the beam radiation on a surface and the normal to that surface, it is defined as

$$cos\theta = sin\delta \, sin\emptyset \, cos\beta - sin\delta \, cos\emptyset \, sin\beta \, cos\gamma + cos\delta \, cos\emptyset \, cos\beta \, cos\omega + cos\delta \, sin\emptyset \, sin\beta \, cos\gamma \, cos\omega + cos\delta \, sin\beta \, sin\gamma \, sin\omega \quad (3)$$

where δ is declination angle which is the angular position of the sun at solar noon. It is can be computed for the day number (nd) such as

$$\delta = 23.45 \sin\left(360 \frac{284+n_d}{365}\right) \quad [21] \quad (4)$$

$\emptyset$ is latitude angle, it is the cite angular location north or south of the equator (33.3°).
β is slope angle, it is the angle between the surface in question and the horizontal. It is adopted as (31°) in this work (as close as possible to latitude angle).
γ is a surface azimuth angle, it is the deviation of the projection on a horizontal plane of the normal to the surface from the local meridian (0 for south).
ω is hour angle, it is the angular displacement of the sun east or west of the local meridian due to the rotation of the earth about its axis at 15° per hour. It is given as

$$\omega = t * \left(\frac{15^o}{1\,h}\right) \quad (5)$$

where (t) is solar time (h). θ_z is a zenith angle of the sun, it is presented as

$$cos\theta_z = cos\emptyset \, cos\delta \, cos\omega + sin\emptyset \, sin\delta \quad (6)$$

3.2 Freshwater Productivity

Rate of freshwater productivity is calculated as

$$m_{ev} = \frac{Q_{ev,w-g}}{h_{fg}} * 3600 \quad (7)$$

where $Q_{ev,w-g}$ is the evaporative heat transfer between the water surface and glass cover. Malik *et al.,* [22] supposed that water vapor complies the perfect gas equation and presented the expression for evaporative heat transfer rate as

$$Q_{ev,w-g} = h_{ev,w-g} \, A_w \, (T_w - T_g) \quad (8)$$

A_w is an area of water over the absorber plate.
T_w is water temperature (°C).
T_g is glass cover temperature (°C).
The evaporative heat transfer coefficient $h_{ev,w-g}$ (W/m^2.K), is Malik *et al.,* [22]

$$h_{ev,w-g} = 0.01623 \, h_{c,w-g}\left(\frac{P_w - P_g}{T_w - T_g}\right) \quad (9)$$

The convective heat transfer coefficient $h_{c,w-g}$ (W/m^2.K), is given as Dunkle [22]

$$h_{c,w-g} = 0.884 \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273)}{(268.9 * 10^3 - P_w)}\right]^{1/3} \quad (10)$$

where P_w and P_g are partial water pressures at temperatures of water and glass cover respectively, they are evaluated as

$$P_w = exp\,[25.317 - \frac{5144}{T_w+273}] \quad (11)$$

$$P_g = exp\,[25.317 - \frac{5144}{T_g+273}] \quad (12)$$

h_{fg} is Latent heat of water vaporization (W/m^2.K) given as Tabrizi [23],

$$h_{fg} = 2.4935\,(106 - 947.79\,T_i + 0.13132\,T_i^2 - 0.0047974\,T_i^3 \qquad \text{for } T_i \leq 70 \quad (13)$$

$$h_{fg} = 3.1615\,(106 - 761.6T_i) \qquad \text{for } T_i > 70 \quad (14)$$

where

$$T_i = \frac{T_g + T_w}{2} \quad (15)$$

3.3 Thermal Efficiency

The thermal efficiency of the distillator is the ratio of condensation heat transfer to the incident solar radiation for unite area can be evaluated as follows

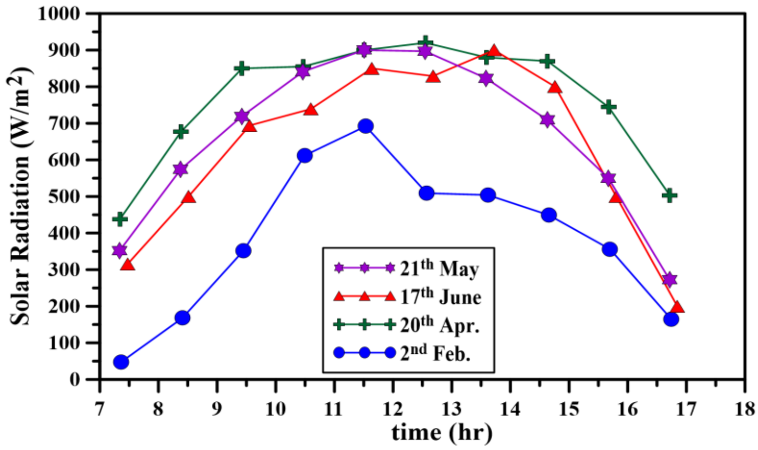
$$\eta_{th} = \frac{Q_{ev,w-g}}{A_p\, G_T} \quad (16)$$

where A_p is the area of absorber plat in which

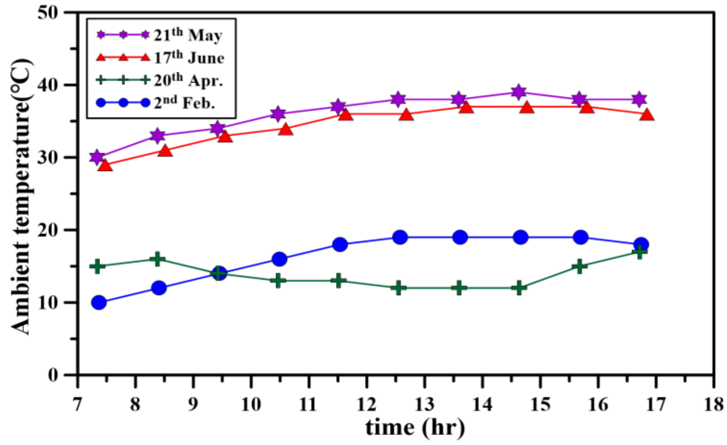
$$Q_{ev,w-g} = \frac{m_{ev} h_{fg}}{3600} \quad (17)$$

4. Results and Discussion
4.1 Ambient Conditions

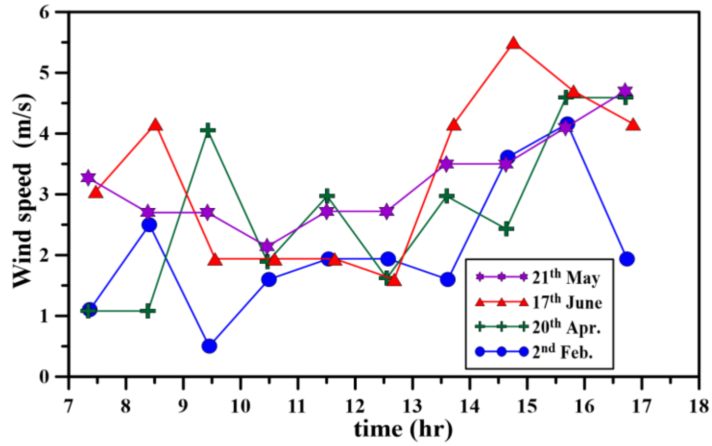
The environmental condition as solar radiation, ambient temperature, and wind speed during the tests of the distillators from February to July 2019 in Baghdad for conventional, stepped and the distillator with floating absorber as shown in Figure 5.



(a)



(b)



(c)

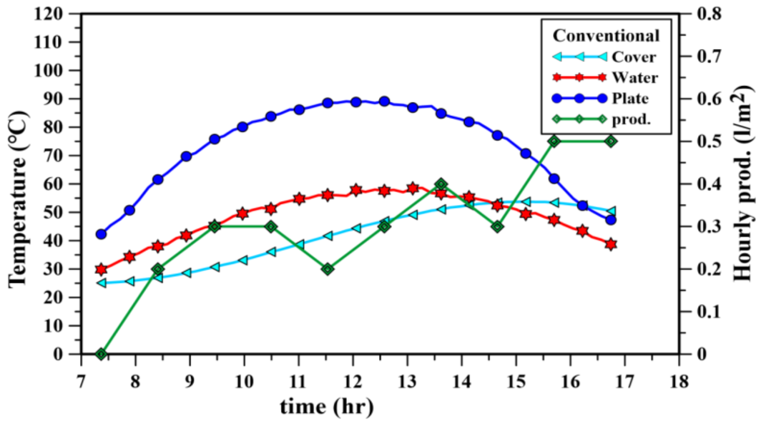
Fig. 5. Environmental conditions on Feb., Apr., May, and June (a) incident solar radiation, (b) ambient temperature and (c) wind speed

4.2 Temperature Variation within the Distillator

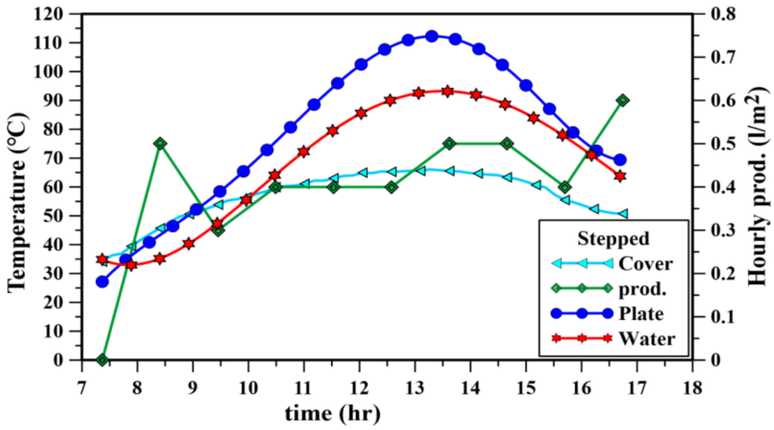
A side by side test on conventional distillator, stepped distillator and the distillator with floating absorber was performed on June 2019 to cover the effect of different designs to specify the highest water productivity. The water level in the conventional distillator and the distillator with floating absorber was (30 mm), (5 mm) heights of prominent parts of the wicks (cotton ribbons) over absorber plate and the perforated plate was in touch with the water surface and (3 l/min) flow rate for stepped solar distillator. These conditions are adopted to compare their behavior in terms of productivity and efficiency.

Figure 6(a) and 6(b) illustrates the hourly temperature variation for water, glass cover, absorber, and hourly water productivity for the conventional and stepped solar distillators for 30 mm water depth in conventional distillator and 3 l/min water flow rate for stepped distillator. It is indicated that the hourly temperature distribution for glass cover, water, and absorber is higher for the stepped solar distillator. A considerable absorber temperature increase is viewed until 13:00 for modified still compared with the conventional still since the absorber plate has a larger surface area due to form the steps. The same behavior is indicated for water and productivity.

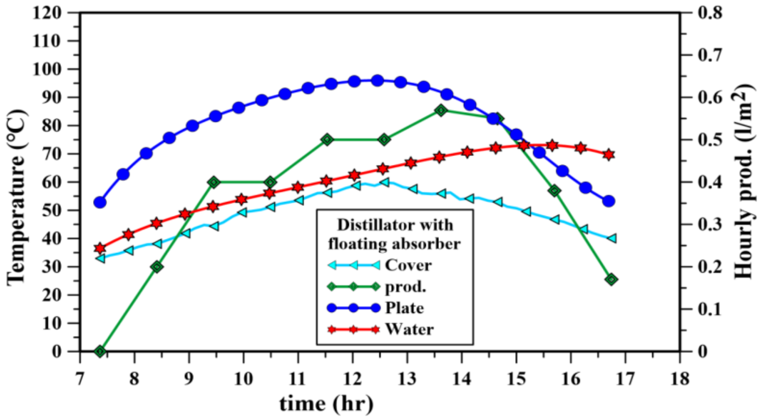
Figure 6(c) illustrates hourly temperature variation for water, glass cover, absorber and hourly water productivity for solar distillator with floating absorber. From a comparison of Figure 6(c) with Figure 6(a) it is found that the hourly temperature distribution for glass cover, water, and absorber is higher for the solar distillator with the floating perforated absorber. A considerable absorber temperature increase is viewed till 13:30 for the modified distillator compared with the conventional still since it is located above the water layer, not beneath it i.e. a thermal resistance formed by this layer is abolished. The same behavior is indicated for water and productivity.



(a)



(b)



(c)

Fig. 6. Hourly variation of cover, water, absorber plate temperatures and productivity on 17th June for: (a) conventional distillator, (b) stepped distillatory and (c) the distillator with floating absorber

4.3 Thermal Performance

Figure 7 shows a comparison between the efficiency of the conventional distillator, stepped distillator and the distillator with the floating absorber. illustrates that all distillators have zero thermal efficiencies since no productivity of freshwater is obtained at the first day time, then they rise since the water productivity rises with increasing of the incident solar radiation. Note that the efficiency of the stepped distillator is 36.19% higher than that of the conventional distillator. The efficiency of the distillator with the floating absorber is higher than that of the conventional distillator by 26%. The efficiency of the stepped distillator is 32.9% is higher than that of the distillator with the floating absorber. Thus, the thermal efficiency reaches maximum values then gradually decayed. It is found that the stepped distillator has higher efficiency, followed by distillator with floating absorber then the conventional type.

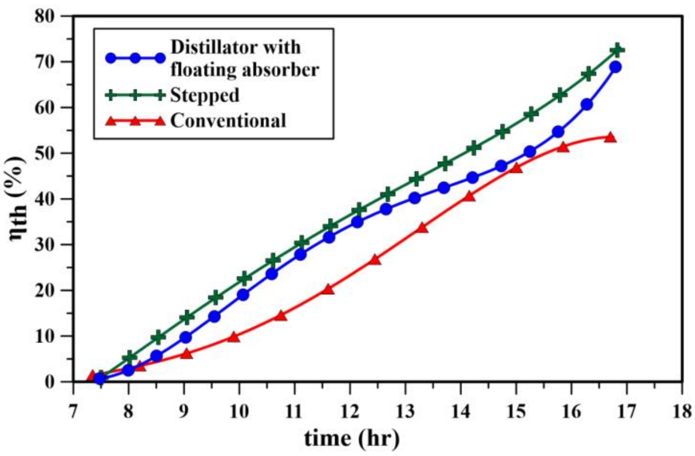


Fig. 7. Thermal efficiency variation of conventional, stepped and the distillator with floating absorber on 12th of June

The accumulated productivity is displayed within 24 hours for the conventional distillator, stepped distillator and the distillator with the floating absorber as shown in Figure 8. There is a noticeable increase in productivity during the night time for all distillators due to stored energy in the thermally insulated basin that feeds the required latent heat of evaporation, and since the temperature of the glass cover decreases after sunset, which helps to increase the condensation process and thus increase productivity. The daily productivity of the stepped distillator is higher than that of the conventional distillator by 30%. The daily productivity of the distillator with the floating absorber is higher than that of the conventional distillator by 16%. The daily productivity of the stepped distillator is higher than that of the distillator with the floating absorber by 11.8%.

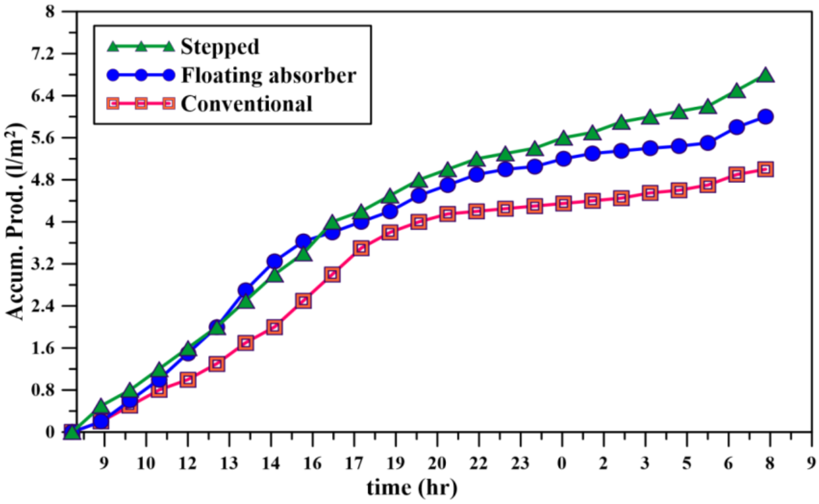


Fig. 8. Daily productivity of conventional, stepped, and distillator with floating absorber on 13th of June

A survey of thermal performance of previously tested distillators and the present distillators are given in Table 4. Good agreement is obtained between their distilled water productivity.

Table 4
Comparison of other studies with the current study

Type of solar still			Remarks	Productivity l/m²	Site location	Ref.
Stepped solar distillator	Current study	Passive	Simple-basin solar distillator	3	Iraq	-
		Passive	Inclined a floating perforated absorber insert wicks (cotton ribbons)	3.5		-
		Active	Inclined copper stepped solar distillator	4		-
Stepped solar still		Passive	Inclined stepped solar still	3.542	Malaysia	[13]
Inclined solar still		Passive	Stepped absorber with sponge	4.73	India	[24]
			Stepped absorber with water coral	5.24		
			Stepped absorber with wood pulp	3.83		
			Flat absorber with sponge	4.186		
			Flat absorber with water coral	4.846		
			Flat absorber with wood pulp	3.3		
Single slope Solar still		Passive	Single slope solar still coupling with a flat-plate collector	3.51	Jordan	[25]
Stepped solar still		Passive	Inclined stepped solar still with internal reflectors	5.84	Egypt	[26]

5. Conclusions

As an effort to improve the productivity and efficiency of the conventional solar distillator, two types of solar distillators, a stepped solar distillator, and a distillator with floating absorber were designed and manufactured. A comparison was made between the performance of conventional distillator, stepped distillator and the distillator with floating absorber by outdoor testing under the climatic conditions of Iraq. Per the previous discussion of the obtained results for the performance of the distillators, important conclusions are extracted

i. Higher daily productivity and efficiency of the stepped distillator are indicated than that for conventional solar distillator by 30% and 36.19% respectively.
ii. Daily productivity and thermal efficiency for the distillator with the floating absorber are higher by 16% and 26% respectively than that for the conventional distillator.
iii. Daily productivity and the efficiency of the stepped distillator are higher than that for the distillator with floating absorber by 11.8 % and 32.9 % respectively.
iv. The stepped distillator viewed higher productivity and efficiency than the conventional distilled and the distillator with the floating absorber.
v. Good agreement is obtained between the previous reported and present distilled water productivity.

Acknowledgment

We gratefully acknowledge to the Ministry of Higher Education and Scientific Research/University of Baghdad for its support.

References

[1] Nagarajan, P. K., S. A. El-Agouz, Harris Samuel DG, Md Edwin, B. Madhu, Ravishankar Sathyamurthy, and R. Bharathwaaj. "Analysis of an inclined solar still with baffles for improving the yield of fresh water." *Process Safety and Environmental Protection* 105 (2017): 326-337.

[2] Kabeel, A. E., and Ali M. Almagar. "Seawater greenhouse in desalination and economics." In *Seventeenth International Water Technology Conference, IWTC17*. 2013.

[3] Muftah, Ali F., Kamaruzzaman Sopian, and M. A. Alghoul. "Performance of basin type stepped solar still enhanced with superior design concepts." *Desalination* 435 (2018): 198-209.

[4] Kabeel, A. E., Y. A. F. El-Samadony, and Wael M. El-Maghlany. "Comparative study on the solar still performance utilizing different PCM." *Desalination* 432 (2018): 89-96.

[5] Feilizadeh, Mehrzad, Mohammad Soltanieh, MR Karimi Estahbanati, Khosrow Jafarpur, and Seyedeh-Saba Ashrafmansouri. "Optimization of geometrical dimensions of single-slope basin-type solar stills." *Desalination* 424 (2017): 159-168.

[6] Mohammed S. S. A., S. Fatihahb, A.E. Kabeel. "Seawater desalination using inclined stepped solar still with copper trays in a wet tropical climate." *Desalination* 423 (2017): 141–148.

[7] Murugavel, K. Kalidasa, and K. Srithar. "Performance study on basin type double slope solar still with different wick materials and minimum mass of water." *Renewable Energy* 36, no. 2 (2011): 612-620.

[8] Lorente, S., A. Bejan, K. Al-Hinai, A. Z. Sahin, and B. S. Yilbas. "Constructal design of distributed energy systems: Solar power and water desalination." *International Journal of Heat and Mass Transfer* 55, no. 9-10 (2012): 2213-2218.

[9] Panchal H. N., Shah P.K. "Investigation on performance analysis of a novel design of the vacuum tube-assisted double basin solar still: an experimental approach." *International Journal of Ambient Energy* 37, (2014): 220-226.

[10] Hamed O. A., Kosaka H., Bamardouf K. H., Al-Shail K., Al-Ghamdi A. S. "Concentrating solar power for seawater thermal desalination." *Desalination* 396, (2016): 70-78.

[11] Rashidi S., Rahbar N., Valipour M. S., Esfahani J. A. "Enhancement of solar still by reticular porous media: Experimental investigation with exergy and economic analysis." *Applied Thermal Engineering* 130, (2017): 1341-1348.

[12] Abd-ur-Rehman H. M., Shakir S., Atta-ur-Razaq, Saqib H., Tahir S. "Decentralized and cost-effective solar water purification system for remote communities." *Earth and Environmental Science* 154, (2018): 1-6.

[13] Abujazar, Mohammed Shadi S., S. Fatihah, E. R. Lotfy, A. E. Kabeel, and Suraya Sharil. "Performance evaluation of inclined copper-stepped solar still in a wet tropical climate." *Desalination* 425 (2018): 94-103.
[14] Wissam H. Alawee. "Improving the productivity of single effect double slope solar still by simple modification", *Journal of Engineering* 21, (2015): 50-60.
[15] Sarhaddi, Faramarz. "Experimental performance assessment of a photovoltaic/thermal stepped solar still." *Energy & Environment* 29, no. 3 (2018): 392-409.
[16] Singh, H. N., and G. N. Tiwari. "Monthly performance of passive and active solar stills for different Indian climatic conditions." *Desalination* 168 (2004): 145-150.
[17] Bergman, Theodore L., Frank P. Incropera, David P. DeWitt, and Adrienne S. Lavine. *Fundamentals of heat and mass transfer*. John Wiley & Sons, 2011.
[18] Shukla S.K., Al-Hamadani A. A. F. "Water distillation using solar energy system with lauric acid as storage medium", *International Journal of Energy Engineering* 1, (2011): 1–8.
[19] J. P. Holman. *Experimental Method for Engineers*. 6th Edition, McGraw-Hill, Singapore City, 1994.
[20] Duffie, John A., and William A. Beckman. *Solar engineering of thermal processes*. New York: Wiley, 1991.
[21] Cooper, P. I. "The absorption of solar radiation in solar stills." *Solar Energy* 12, (1968): 333-46.
[22] Malik, M. A. S., Gopal Nath Tiwari, Arun Kumar, and M. S. Sodha. *Solar distillation: a practical study of a wide range of stills and their optimum design, construction, and performance*. Oxford: Pergamon press, 1982.
[23] Tabrizi F. F., Dashtban M., Moghaddam H., Razzaghi K. "Effect of water flow rate on internal heat and mass transfer and daily productivity of a weir-type cascade solar still." *Desalination* 260, (2010): 239-247.
[24] R. Samuel Hansen, C. Surya Narayanan, K. Kalidasa Murugavel. "Performance analysis on inclined solar still with different new wick materials and wire mesh." *Desalination* 358, (2015): 1–8.
[25] Badran O.O., Al-Tahaineh H.A. "The effect of coupling a flat-plate collector on the solar still productivity." *Desalination* 183, (2005): 137–142.
[26] Z.M. Omara, A.E. Kabeel, M.M. Younes. "Enhancing the stepped solar still performance using internal reflectors." *Desalination* 314, (2013): 67–72.