Mechanical and Energy Engineering

Experimental Investigation of a Single Basin -Single Slope Solar Still Coupled with Evacuated Tube Solar Collector

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ABSTRACT

This work is an experimental investigation for single basin-single slope solar still coupled with an evacuated tube solar collector. The work is carried out under the climatic conditions of Baghdad city (33.2456º North and East latitude, 44.3337º longitude) through certain days of the months of the year 2019 to study the impact of using evacuated tube solar collector on the daily productivity and efficiency under the outdoors climatic conditions. It was found that using the evacuated tube solar collector increase daily productivity from 2.175 kg/m^2 to 2.95 kg/m^2 for 9 hours (35.63 %) for clear days, also an enhancement about 10.97 % in daily efficiency.

Keywords: Desalination, solar still, ETC-evacuated tube collector, productivity.

تحقيق تجريبي لمقطر شمسي احادي الحوض−احادي الميل مرتبط بمجمع انابيب مفرغة

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الخلاصة

هذا العمل عبارة عن تحقيق تجريبي لمقطر شمسي أحادي الحوض-احادي المنحدر مقترن بمجمع الانابيب الشمسية المفرغة. تم تنفيذ العمل في ظل الظروف المناخية لمدينة بغداد (33.2456 درجة شمال وخط عرض شرق ، 44.3337 خط طول) خلال أيام معينة من أشهر سنة 2019 لدراسة تأثير استخدام مجمّع الأنابيب الشمسية المفرغة على الإنتاجية والكفاءة اليومية للمقطر تحت الظروف المناخية في الهواء الطلق. وجد أن استخدام مجمّع الأنابيب الشمسية المفرغة يزيد الإنتاجية اليومية من 2.175 kg/m^2 إلى 2.95 kg/m^2 لمدة 9 ساعات (35.63٪) للأيام الصافية، وكذلك تحسن بنسبة 10.97٪ في الكفاءة اليومية.

الكلمات الرئيسية: تحلية المياه, مقطر شمسي, مجمع الانابيب المفرغة, الانتاج

1. INTRODUCTION

The salty water is supplied to the basin in conventional solar desalination. There is a tilted cover transparent to solar radiation covering the basin, and the water condenses at that cover is obtained by a channel. The primary cost of solar still is at the beginning of financing (**Mohanad, 2016**). Solar still is a suitable solution for remote areas, but it is like any desalination method having advantages and disadvantages; it is uncomplicated in design, do not demand a skilled operator, environment friendly, non-polluting, so it is an easy way, low expense, effective way of providing clean water in houses or a miniature community when the water demand is small. But it must be taken into account that this method relies on the weather circumstances, and it needs a large area for high production. Solar still can be classified into two major groups: A- Passive solar still, which means desalination of water with direct solar energy, it is a traditional system in which solar energy is utilized as a single source of thermal energy (**Qiblawey** and **Banat, 2008**). B- Active solar still, in this type, the solar still combined with a solar concentrator or heater, is usually indicated as an active solar distillation (**Qiblawey** and **Banat, 2008**). Active systems employ valves, electric pumps, and controllers to flow water or another heat-transfer liquid in the collectors. Active systems usually are more expensive than passive systems, but they are more effective. (**Foster, et al., 2010**).

Many studies have been done to investigate solar still productivity. (**Tarawneh, 2007**) studied the effect of the depth of water in the basin on productivity and verified the effect of the design and operation elements on the water desalination process. A small desalination system was established and operated, and several water depths were tried (0.5 cm, 2 cm, 3 cm, 4 cm), and the amount of total dissolved solids in it was 5,000 ppm. The study lasted for about six months. It was proven that the desalination process is strongly affected by weather conditions and elements of design and operation where production decreases with increasing water depth and production is closely related to falling solar radiation. (**Khalifa and Hamood, 2009**) the effect of the amount of insulation thickness on the productivity of the solar still has been studied. The test was performed with several thickness dimensions (30 mm, 60 mm, and 100 mm). The results were compared with the solar still without insulation. It was found that insulation has a significant role. For example, when the thickness is 60 mm, the productivity increased by 80% due to an increase in the operating temperature which is caused by isolation.

(**Khalifa, 2011**) studied the effect of the cover angle on the productivity of the solar still in many seasons in conjunction with the relationship between the optimum tilt angle and the latitude angle. It was conducted that increasing the inclination angle increases the solar output still during the year; the angle is preferably high in winter and lower in summer. When the latitude angle is high, it is preferable to increase the angle of slope of the cover when experimenting. (**Azooz and Younis, 2016**) studied the effect of the angle of inclination of the glass cover on the performance of the solar still. The study was conducted on ten solar stills, different inclination angle for each still starts from 15° to 55°, i.e., a difference of 5° for each solar still. The results showed that the angles between 30° to 35° gave low performance to the solar stills while the angles between 20° to 25° were related to the best performance of the stills. Empirical modeling of the still process gave satisfying agreement.

(**Hammadi and Jasim, 2019**) studied the effect of both thermal insulation and the level of water inside the solar still on productivity and tested the distillation process at night. In this study, a single- basin single-slope solar still was used for a period of about four months, and the results

showed that productivity increased by more than 20.7% with a depth of 4 cm and 19.8% with a depth of 5 cm with thermal insulation. In the case of non-isolation, productivity is reduced by 14.14%, and distillation during the evening has an importance that cannot be overlooked. **(Badran and Al-Tahaineh, 2005)** studied the effect of attaching a flat plate collector with solar still on its productivity in addition to some other factors such as solar radiation, the depth of water inside the basin, the direction of the still, and how to improve it through them. A single-slope solar still equipped with mirrors fixed in its inner sides were used, and the still was connected to a flat plate collector, which increased productivity to about 36%, noting that the solar radiation is proportional to productivity and that increasing water depth affects negatively on it. **(Arunkumar,et al., 2010)** investigated the effect of linking the single-slope solar still with a compound parabolic concentrator (CPC). The experiment was conducted for two months, January and February of the year 2010. The unique thing in this design is that the absorbent in the shape of a crescent is in the focus of the parabolic concentrator and its entrance and exit are linked to the single-slope solar still. The performance of the study was analysed through two modes: the coupling of the solar still with the crescent absorber from under the closed cap to avoid the solar radiation entering the slope. The second is to make the solar still open to allow solar radiation to enter it. The area of the solar still was about 0.25 m^2. System temperatures such as water temperature, air temperature, the temperature of the outer and inner covers were measured by k-type thermocouples and digital thermometers. Wind speed and humidity measurements were also recorded. Instantaneous efficiency and hourly output were calculated and there was noticeable progress in the results.

(Chaouchi, et al., 2007) used the parabolic concentrator to increase the temperatures that make the water inside the basin evaporate faster and with equal pressure or slightly above air pressure**.** A small laboratory desalination system attached to the parabolic concentrators was designed and manufactured in addition to developing a mathematical model to calculate the average absorber temperature and the flow rate of distilled water as a function of solar radiation. **(Panchal, 2013)** designed a double-slope solar still, the upper basin with dimensions of 1006 mm ×536 mm × 100 mm and the lower basin is 1006 mm × 325 mm × 380 mm. Several cases have been studied, double-slope solar still alone, double-slope solar still with black granite stone, double-slope solar still with vacuum tubes, and double-slope solar still with vacuum tubes and black granite stone. Black granite stone is used to reduce the amount of saltwater inside the basins and thus increase productivity. Through these experiments, it is observed that productivity increased by 56% when using vacuum tubes only and 65% when using vacuum tubes with black granite stone. **(Elgohary** and **Abd Elfatah, 2016)** conducted an experimental study of the solar desalination system when connected with the flat plate collector. By comparison between the solar still alone and the solar still with the flat plate, it was found that the production for the still alone is 2.28 L/m^2 and for ten hours, while the still connected to the flat plate was 1.56 L/m^2 for the same period, these results were in the case of strong solar radiation. Therefore, the flat plate collector is effective in low heat and radiation intensity since the output temperature from the flat plate is less than the temperature of water in the basin of inactive still. Unlike vacuum tubes, they improved production to 6.45 L/m^2 for 12 hours. The theoretical side was using the Matlab program and by entering the weather data for January and March in Suez Governorate. The results ranged between 1 L/m^2/day in January to 3 L/m^2/day in March. The experimental and theoretical results showed a good match. **(Bandhu, et al., 2020)** explain the effect of the mass flow rate of water on the life cycle of the conversion efficiency of the single-slope solar desalination system joined with N-identical evacuated tube collectors. The analysis process took place within days in May and December in the weather conditions of New Delhi and with the help of an analytical program conducted in Matlab, the

information used in numerical calculations was taken from the Department of Meteorology in India. The average annual value of energy emitted was calculated based on the energy outputs in the summer and winter seasons and then evaluating the conversion efficiency life cycle. Where it was found that it decreases at the height of the fluid flow mass per unit of time and remains almost constant when exceeding 0.044 kg /s and at specific values for the depth of the water and the number of collectors as it has a similar tendency to any other number of collectors.

 (**Alawee, 2015**) conducted an experimental study to improve the performance of the single-effect double-slope solar still by making a simple change in the design, which is to enlarge the dimensions of the still compared to the dimensions of the basin to increase the condensation process without using any means, in addition to attaching solar reflective panels to the base of the still, Productivity improved in this way by a value ranging from 18 to 24%. (**Hammadi and Jasim, 2019**) conducted practical tests to clarify the effects of the depth of water inside the still basin and its thermal insulation. Tests were conducted in the weather conditions of the city of Mosul from May to August and for several water levels of 4 and 5 cm. The productivity increased to 19.864% and 20.785% when the depth of the water was 5 and 4 cm, respectively, with the presence of thermal insulation, but in the absence of it, the productivity decreased to 14.147%.

The current research aims to study a single slope -single basin solar still system after the using of the evacuated tube solar collector within the system by connecting it to the still to take advantage of the hot water provided from it to accelerate the process of water evaporation even before the still was exposed to solar radiation for a long time and this maintains a moderate temperature for the glass cover from the outside, which Also increases condensation process.

2.EXPERIMENTAL SETUP AND SOLAR STILL DESCRIPTION

The basis for the operation of solar still is simple. The distillation basin containing the brine absorbs the solar energy from the sun, and the water evaporates, leaving the salts and pollutants in the basin due to their inability to evaporate. Water vapor begins to rise due to convection currents due to the difference between the water and the glass temperature. When contact occurs between this vapor and the glass that represents the condensation surface, the vapor will begin to condense in the form of drops because the condensation surface is relatively cooler than the rising water vapor, the water drops slide as a result of the Earth's gravity to be collected through the water collection channel. To ensure the reliability of the results, two solar stills were made with the same size, specifications, and materials were used to work in conjunction with each other, the first is a conventional still, and the other is related to the vacuum tubes collector as it helps to provide the still with preheated water to accelerate the evaporation of water inside the basin, **Table 1** represents the specifications of the two stills.

The solar still was manufactured from several locally manufactured materials with a relatively low cost, based on previous research. The materials were select. These researches were also adopted to determine the best design in choosing the basin material and cover and its angle of inclination and insulation. The basin was formed of galvanized iron (GI sheets), the thickness of the sheet used is (1.5 mm), basin dimensions were (1 m x 0.5 m), that is, the area of the basin is 0.5 m^2. The basin interior is painted in a matte black colour to increase its absorption of sunlight, thereby raising the temperature of the water inside the basin and causing an increase in the temperature difference between the water and the temperature of the still cover, which is the condensed surface, thus increasing the condensation rate (**Srivastava** and **Agrawal, 2012**). As for the degree of

inclination of the basin cover, it must be suitable to ensure that the water does not return to the basin so that it can flow down the inner surface of the cover and the angle also affects the optimal use of solar radiation. The degree of slope adopted was 33.34° (it is almost equal to the latitude of Baghdad). The distillation channel is used to collect distilled water and transfer it outside the basin, it was made of the same material that the basin was made of, which is the GI sheet, with (0.5 m x 0.02 m x 0.03 m), it is small in order not to cause the formation of shade on the distiller basin. Cork sheets were used in this work with a thickness of 6 cm and thermal conductivity of 0.04-0.055 W/m. °K **(Istek, 2019)** as the first layer of insulation and plywood panels have a thickness of 1.1 cm with a thermal conductivity coefficient of 0.08-0.16 W/m. °K were used as a second layer.

Compared to glass with a thickness of 6 mm, 8 mm, or even 12 mm, the most appropriate thickness is 4mm because its condensation temperature is the lowest **(Panchal and Shah, 2011). T**herefore, this thickness has been used in the present work. Galvanized iron pipe with a 1.27 cm diameter was used to introduce water from the source into the solar. And another pipe with the same specifications was used at the bottom of the still to get rid of the remaining water after each experiment or empty the water used to clean the still from time to time. A schematic diagram of the solar still is shown in **Fig.1**.
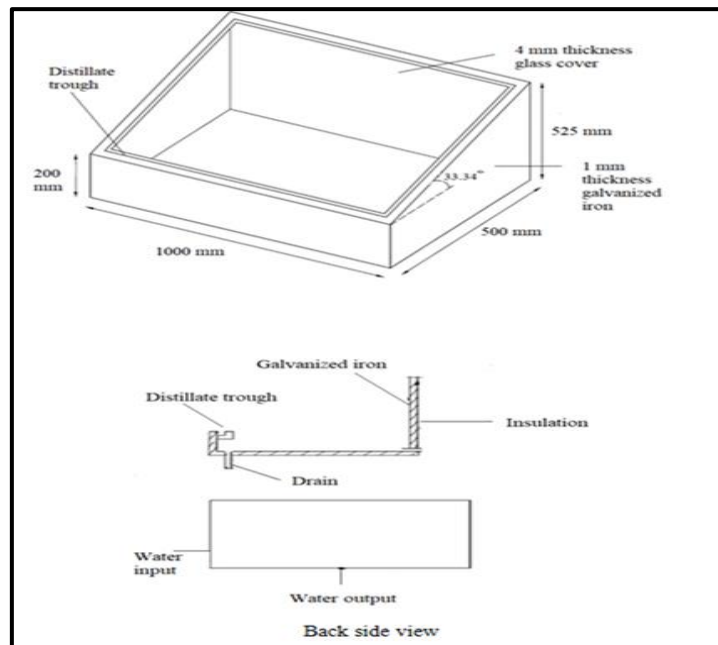

Figure 1. Schematic diagram of solar still.

Table 1. Structural components of the solar still.

Still Design	Basin	GI sheet 1.5 mm thickness Length 1 m, Width 0.5 m
	Basin cover	Glass, 4mm thickness Tilt angle 33.34°
	Insulation	Cork sheets 6 cm thickness Plywood 1.1 cm

Evacuated tubes solar collector used in the current work consisted of 30 vacuum tubes of 1800 mm length and 2.6 liters capacity. Each tube was made of two glass tubes one inside the other. It was made of strong borosilicate glass 3.3, with 1.6 mm thickness, the outer tube (evacuated glass tube) is 58mm in diameter, transparent to allow sunlight to pass through, while the inner tube (heat tube) is 47mm in diameter, covered with special selective material with excellent sunlight absorption and little reflection (Nitrite Aluminium) and contains water to be heated with solar energy. The ends of the tubes are settled together by the fusion process after the air between them is emptied under high temperature, discharging air between the two tubes generates a vacuum insulation zone, as the vacuum is one of the best types of insulators since the air conveys heat inside and outside. These tubes are connected with a thermally isolated horizontal cylindrical tank with a capacity of 263 liters, as shown in **Fig.2**.The tank is divided into two areas, the upper where the hot water rises, the lower where the cold water settles, as the cold water is replaced by hot water through natural convection. **Table 2** shows the design specifications of the evacuated tube solar collector until the produced hot water accumulates inside the cylindrical tank. The temperatures were recorded by using thermocouples (type k, operate at temperatures up to 2,500 degrees Celsius and have lengths of two meters) connected to 8 channel data logger with SD card produced by (Lutron Company of Taiwan model BTM - 4208SD). Thermocouples are set at different locations, and those locations are the outer surface of the glass cover at three points, the center, the lower left, the upper right. They are affixed to the glass with a superior weather-proof and waterproof epoxy and wrapped with a white PVC strip around each thermocouple to prevent exposure to sunlight. From the inside, the temperature of the cover from the middle, the inner space, water, the basin plate, and the plate under the water was recorded, as for the thermocouple sheathed with metal used to measure the temperature of the basin plate, it is placed inside an iron tube. It is welded to the base of the basin so that it does not touch the water and the thermocouple sheathed with metal used to measure the water temperature is placed inside an iron tube and placed one centimeter higher than the basin plate and is submerged in water.

An additional thermocouple is used to measure the ambient temperature placed in the shade behind the still so that it would not be affected by the sun's rays and at least one meter above the ground to avoid the impact of heat from the ground; this thermocouple is fitted into a flexible, non-

reinforced open-ended tube (internal diameter = 1.2 cm, wall thickness = 0.15 cm, length = 2.5 cm) to allow free movement of air, a schematic diagram of the solar still coupled with evacuated tube collector is shown in **Fig. 3**.

Figure 2. Evacuated solar tube collector.

Table 2. Design specifications of the evacuated tube solar collector.

	Number of tubes	30
	Orientation	South
Evacuated tube solar collector design	Aperture area	3 m²
	Capacity of tank	263 L
	Inner diameter of storage tank	37 cm
	Length of storage tank	2.7 m
	Insulator of tank	Polyurethane foam
	Insulator of collector	Vacuum
	Thickness of insulator	5cm
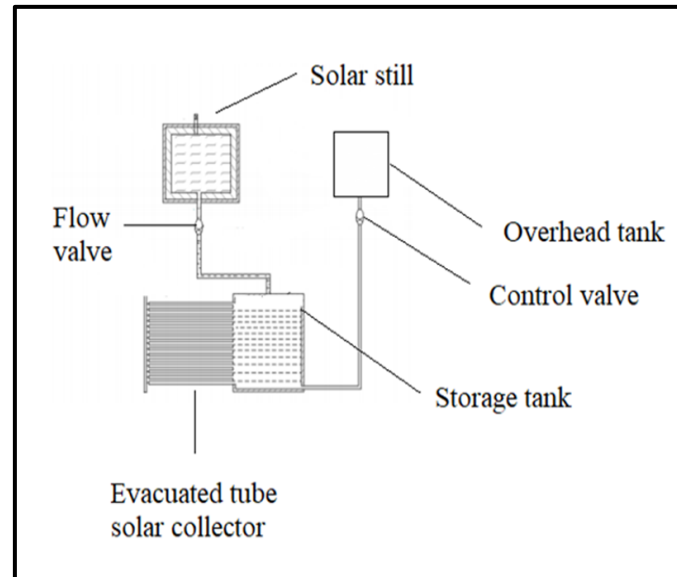
Figure 3. Schematic diagram of solar still coupled with evacuated tube solar collector.

Figure 4. System setup.

3. ANALYSIS WORK

The solar radiation that falls on the solar cover of the solar is partly reflected and the other absorbing. The remainder, which is the greater part, travels through the cover and moves to the water to be absorbed by it and a small part of it is lost as losses through the bottom of the base or the sides. Throughout the analysis, the following assumptions have been used:

1. As the system is tight, there is no leakage of vapour from the system.
2. Water vapour is an ideal gas.
3. The heat capacity of the basin, the glass, and the insulation material are neglected.
4. The area of the glass is equal to the area of the basin ($A = A_g = A_b$).

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5. Due to the small thickness of the glass cover, no temperature gradient across the glass is assumed ($T_g = T_{g\ in} = T_{g\ out}$). Also, no temperature gradients in other components of the still.
6. The water flow rate is regarded to be constant during each experiment.
7. The working pressure outside and inside the solar still is the atmospheric pressure which is 1 bar.

8. There are no heat losses from the sides and bottom of the solar still.

The productivity (daily and hourly) and efficiency of the solar still can be found as follows:

$$\dot{m}_{day} = \sum_{1}^{24} \dot{m} \qquad (\text{kg}/m^2.\text{day}) \tag{1}$$

$$\dot{m} = \frac{h_{e,w-gc}\,(T_w - T_{gc}) * 3600}{h_{fg,w}} \qquad (\text{kg}/m^2.\text{hr})\ \textbf{(Sampathkumar and Senthilkumar, 2012)} \tag{2}$$

$$\eta_{energy\ daily} = \frac{\dot{m}_{day} * h_{fg,ave}}{\sum_{1}^{24} I\,(t) * 3600} * 100\% \tag{3}$$

$$\eta_{energy} = \frac{h_{e,w-gc}\,(T_w - T_{gc})}{I\,(t)} * 100\% \qquad \textbf{(Ranjan, et al., 2016)} \tag{4}$$

$h_{fg,ave}$ = The daily average latent heat

h_{fg} can be found from vapour tables or from the following relation (**Wagner and Pruß, 2002**):

$$h_{fg} = 3044205.5 - 1679.1109\,T_f - 1.14258\,T_f{}^2 \quad (\text{J/kg}) \tag{5}$$

Where:

$$T_f = \frac{(T_w + T_{gc})}{2} + 273.15 \qquad (°k) \tag{6}$$

A- Exergy balance of saline water

The Exergy balance for the saline water can be formed as follows (**Ranjan et al., 2016**):

$$IR_w = (\tau_{gc}\alpha_w)\,EX_{sun} + EX_w - EX_{t,w-gc} \tag{7}$$

$$IR_w = (\tau_{gc}\alpha_w)\,EX_{sun} + EX_w - (EX_{c,w-gc} + EX_{r,w-gc} + EX_{e,w-gc}) \tag{8}$$

Where:

IR_w = Irreversibility of water mass.

EX_{sun} = Exergy due to solar radiation.

EX_w = Accumulated Exergy within the saline water.

$EX_{c,w-gc}$ = Exergy due to the free convection heat transfer from water to the glass cover.

$EX_{r,w-gc}$ = Exergy due to the radiative heat transfer from water to the glass cover.

$EX_{e,w-gc}$ = Exergy due to the evaporative heat transfer from water to the glass cover.

EX_{sun} can be calculated by multiplying (I_t) by the Petela expression (**Lawrence, 2005**):

$$EX_{sun} = I_t\,A * \left[\,1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\,\right] \tag{9}$$

T_s = he solar radiation temperature = sun temperature at 6000 °k

$$EX_w = \frac{m_w c_w}{A}\left(\frac{T_w - T_a}{t}\right)\left(1 - \frac{T_a}{T_w}\right) \tag{10}$$

$$EX_w = h_{c,w-gc}\,A\,(T_w - T_{gc})\left(1 - \frac{T_a}{T_w}\right) \tag{11}$$

$$EX_{e,w-gc} = h_{e,w-gc}\,A\,(T_w - T_{gc})\left(1 - \frac{T_a}{T_w}\right) \tag{12}$$

$$EX_{r,w-gc} = h_{r,w-gc}\,A\,(T_w - T_{gc})\left(1 - \frac{T_a}{T_w}\right) \tag{13}$$

B- Exergy balance of glass cover

$$IR_{gc} = \alpha_{gc}\,EX_{sun} + EX_{c,w-gc} + EX_{r,w-gc} + EX_{e,w-gc} - (EX_{r,gc-a} + EX_{c,gc-a}) \tag{14}$$

(14)

Where:

IR_{gc} = Irreversibility of the glass cover.

$EX_{c,gc-a}$ = Exergy due to convection heat transfer from glass cover to ambient.

$EX_{r,gc-a}$ = Exergy due to radiative heat transfer from glass cover to ambient.

$$EX_{c,gc-a} = h_{c,gc-a}\,A\,(T_{gc} - T_a)\,(1 - \frac{T_a}{T_{gc}}) \tag{15}$$

$$EX_{r,gc-a} = h_{r,gc-a}\,A\,(T_{gc} - T_a)\,(1 - \frac{T_a}{T_{gc}}) \tag{16}$$

C- Exergy balance of basin liner

The exergy balance for the basin- liner can be formed as follows (**Ranjan et al., 2016**):

$$IR_b = (\tau_{gc}\tau_w\alpha_b)\,EX_{sun} - (EX_w + EX_{b,ws}) \tag{17}$$

$$EX_{b,ws} = U_{ins}\,(T_b - T_{ws})\,(1 - \frac{T_a}{T_b}) \tag{18}$$

D- Expressions of exergetic efficiencies

$$\eta_{exergy} = \frac{Exergy\ output\ from\ passive\ solar\ still}{Exergy\ input\ to\ passive\ solar\ still} = \frac{EX_{e,w-gc}}{EX_{sun}} \tag{19}$$

Sub equations (9), (12) in equation (19):

$$\eta_{exergy} = \frac{h_{e,w-gc}\,A(T_w - T_{gc})}{I_t\,A} * \frac{\left(1 - \frac{T_a}{T_w}\right)}{\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right]} \tag{20}$$

Or:

$$\eta_{exergy} = \frac{\dot{m}\,h_{fg,w}}{I_t\,A} * \frac{\left(1 - \frac{T_a}{T_w}\right)}{\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right]} \tag{21}$$

Then

$$\eta_{exergy} = \eta_{energy} * \frac{(T_w - T_a)}{T_w\left[1 + \frac{1}{3}\left(\frac{T_a}{T_s}\right)^4 - \frac{4}{3}\left(\frac{T_a}{T_s}\right)\right]} \tag{22}$$

Equations were resolved by employing solar still design parameters as presented in **Table 3.**

Table 3. Related parameters used in the calculations (**Kabeel, et al., 2012).**

Related parameter	Value
ε_w	0.95
ε_{gc}	0.88
τ_w	0.95
α_w	0.05
α_b	0.95
α_{gc}	0.127
$k_{ins}(W/m.°k)$	0.045
$x_{ins}(m)$	0.03

|	
$C_{p,w}$ (J/kg.°k)	4190
$C_{p,gc}$(J/kg.°k)	800
$C_{p,b}$(J/kg.°k)	896
A_b (m^2)	0.5
k_b(W/m.°C)	73
x_b(m)	0.001
σ(W/m^2.k^4)	$5.67*10^{-8}$
k_b(W/m.°C)	73

4.RESULTS AND DISCUSSION
 To investigate the impact of evacuated tube solar collector or the productivity of single basin-single slope solar still, two similar solar stills as shown in **Fig.4**, the first was passive. At the same time, the second was coupled with the evacuated tube solar collector, stills placed on, oriented to the south, and examined under outside conditions.
Fig.5 shows the solar radiation for a clear sunny day (during June month), the productivity of solar still increased with solar radiation and it is more than in solar still coupled with evacuated tube solar collector as shown in **Fig.6**, from results it was observed that productivity increased from 2.175 kg/m^2 to 2.95 kg/$m^2$for 9 hours which means more than 35.63 % for sunny days.
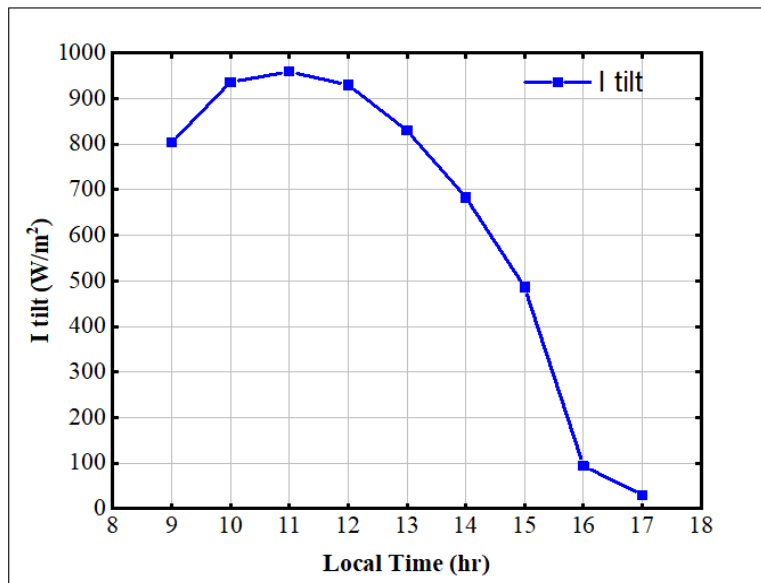

Figure 5.Average solar radiation from 9 AM to 6 PM for a certain day (June-2019).
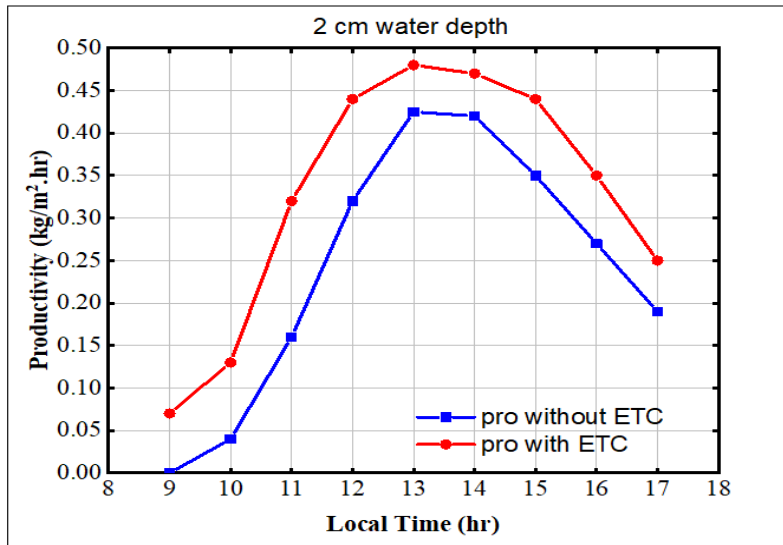
Figure 6. Comparison of the average hourly variation of the still experimental productivity with and without ETC from 9 AM to 6 PM for a certain day (June-2019).

Fig.7 shows the difference in the hourly thermal efficiency of the two solar stills. The reason for the improvement is due to the shortening of the water heating process inside the solar still, where the evacuated tubes provide the still with water at higher temperatures. This accelerates the evaporation and condensation of water inside it, unlike the passive still, which takes a long time until the water is heated and evaporated. Daily productivity increased from 32.94% to 36.55% which means 10.97 % enhancement due to the increase in the amount of water produced for the same amount of solar radiation that the stills are exposed to, as the preheating of the water produced from the evacuated tube collector greatly contributed to improving performance as it increases the rate of water evaporation.
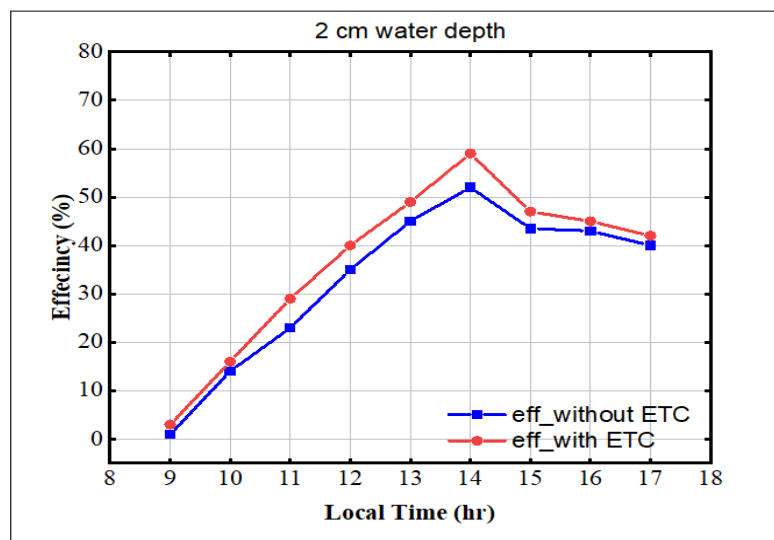
Figure 7. Comparison of the average hourly efficiency of stills with and without ETC for a certain day (June-2019).

Fig.8 shows the average hourly exergy rate variation; exergies increase with the increase of solar radiation intensity because solar energy is still the only source used in solar. As a result, the increased solar radiation will raise the temperature of the water. This leads to an increase in evaporative exergy, which raises distillation productivity.

As for energy and exergy productivity, **Fig.9** shows the comparison between them for still with evacuated tube collector. Results showed that exergy efficiency is much lower than energy efficiency due to the small quantities of the available energy and exergy associated with heat evaporation. Daily energy efficiency is enhanced by 45.31% by using an evacuated tube collector.
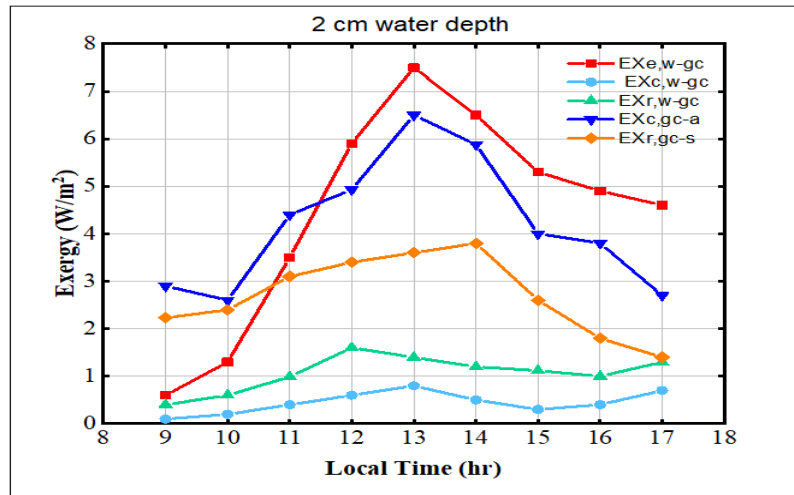

Figure 8. Average hourly variation in exergy rates for still with ETC for a certain day (June-2019).
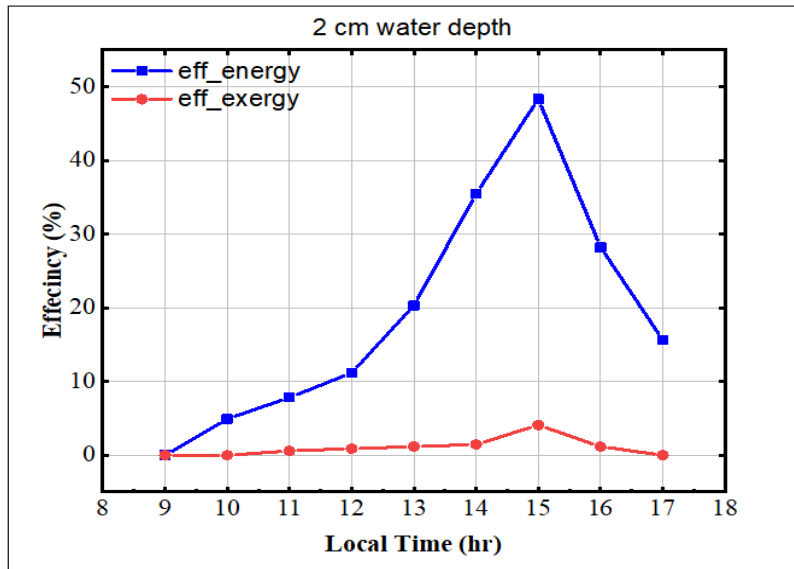

Figure 9. A comparison of average energy and exergy efficiency of still with ETC for a certain day (June-2019).

Fig.10 and **11** show the hourly variation of the water, basin, glass, and ambient temperatures of passive solar still and solar still coupled with evacuated tube collector, respectively. It is obvious

that the temperatures start initially together and then gradually rise as a result of increasing in solar radiation intensity until the temperatures reach their maximum values between 1 and 2 PM, as the daylight can be divided into three intervals, first from 6 AM to 9 AM, the second from 9 AM to 2 PM and the third interval is after 2 PM when the solar radiation decreases and temperatures decrease too. It is evidenced by the figures that basin temperature is slightly more than water temperature due to high thermal conductivity, low transmissivity, in addition to the insulation of the basin to prevent heat leakage into the outside environment, which leads to an increase in the basin temperature.
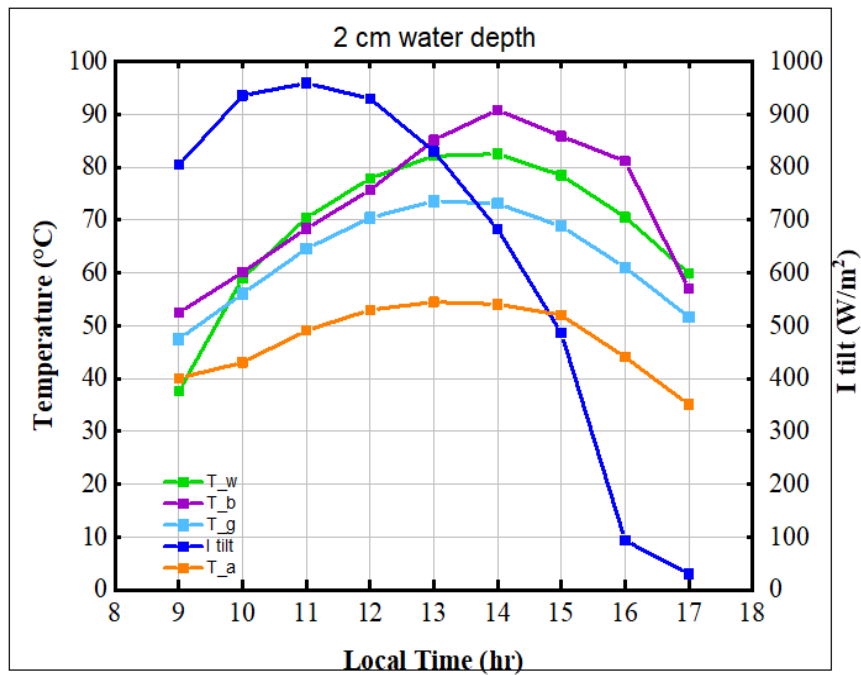
Figure 10. The average experimental difference of temperatures with time for solar still without ETC for a certain day (June-2019).
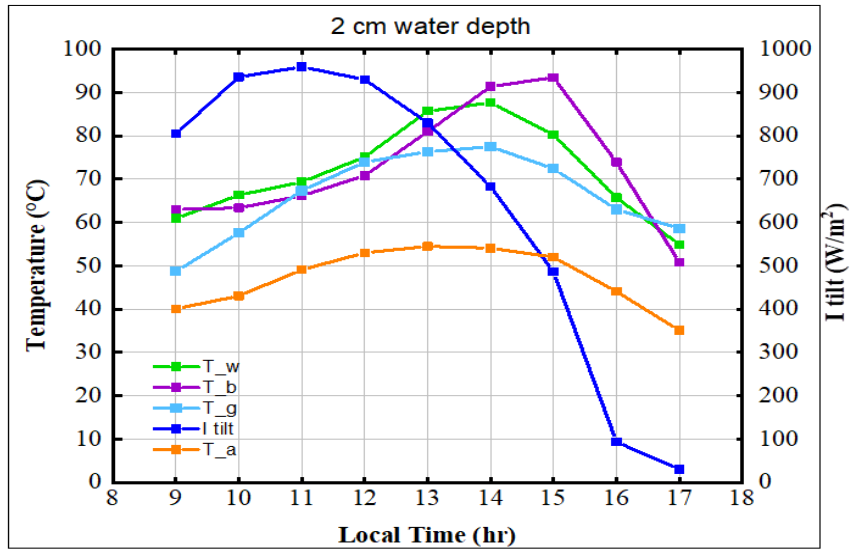
Figure 11. The average experimental difference of temperatures with time for solar still with ETC for a certain day (June-2019).

Fig.12 and **13** show the difference between water and glass temperatures for passive and active still coupled with evacuated tube collectors. It is obvious from the figures that the temperature of the water is higher when the still is connected to the evacuated tubes, as it provides the still basin with preheated water for high temperatures that may reach 90°C as shown in the figure in addition to the glass temperature is lower, which causes the difference between water and glass temperature and that increases the condensation process of the steam rising from the still basin and leads to an increase in still productivity.
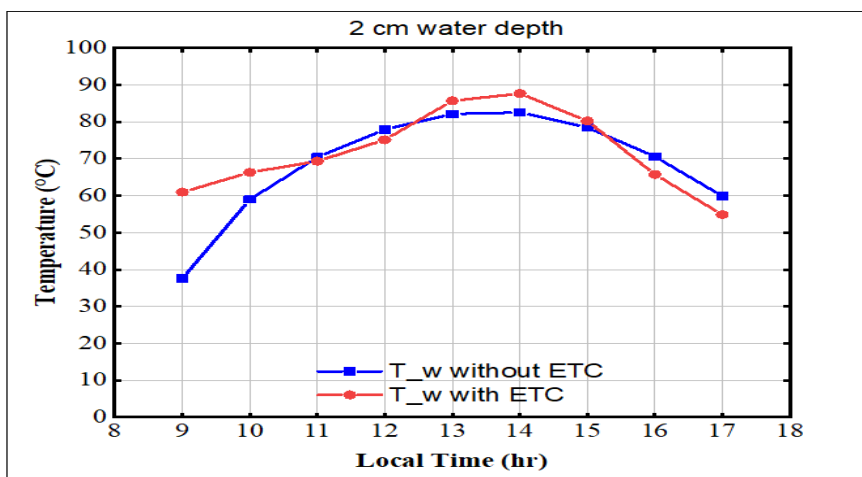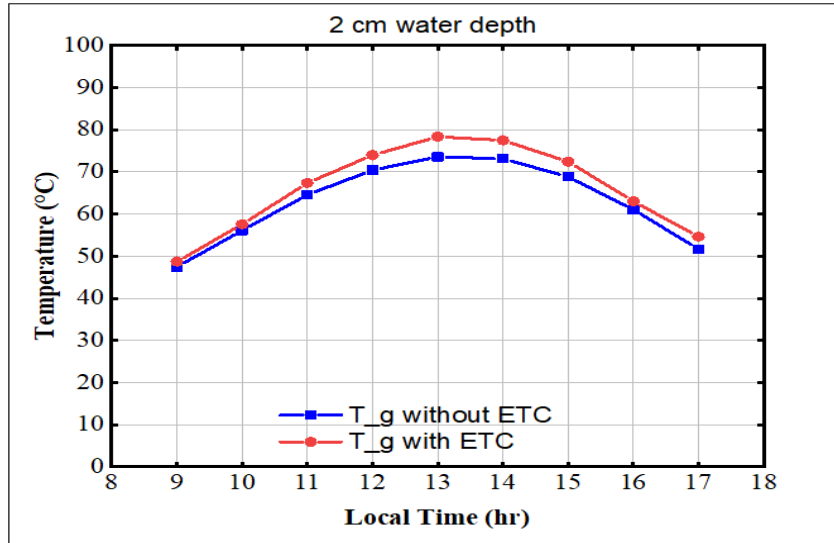

Figure 12. CoA cparison of average experimental variation of temperatures with time for water with and without ETC for a certain day (June-2019).

Figure 13. A comparison of average experimental variation of temperatures with time for glass with and without ETC for a certain day (June-2019).

Fig.14 shows a comparison of the difference in temperatures $(T_w - T_g)$ with time for solar still, with and without evacuated tube collector, the difference with the solar collector is more than passive still. This is one of the main reasons for improving the distilled water production process, as higher water temperature increases, it evaporates and reduces the temperature of the glass, making it a better-condensed surface for that steam because the water distillation process using solar stills depends on the rate of water evaporation and condensation inside those stills.
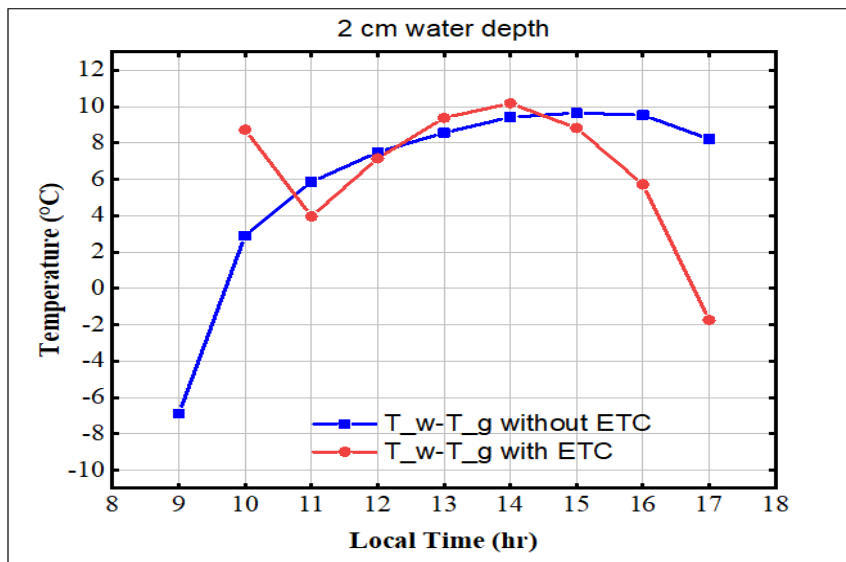
Figure 14. A comparison of the difference in temperatures $(T_w - T_g)$ with time for solar still with and without ETC for a certain day (June-2019).

5.CONCLUSIONS

From the current work, the following can be concluded:

1- The practical results showed the possibility of improving the productivity of the conventional solar still by connecting it to the evacuated tube collector in order to accelerate the evaporation process inside the distillation basin without using any auxiliary means for condensation. Productivity has improved by 35.63% compared to passive still.
2- Weather factors have an important effect on the productivity of the still, especially solar radiation, and this is what distinguishes the site in which the experiments were conducted, which is the city of Baghdad, because it has high solar radiation most days of the year.
3- The largest quantity of exergy in the still is destructing in the basin of a solar still; therefore, efforts must be made to limit this devastation through a well-designed solar basin.

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Nomenclature
Latin Symbols
A = area, m^2.
CP= specific heat, J/kg. K.
E= system solar energy, J.
Ex= exergy flux, W/m^2.
F= view factor, dimensionless.
G= gas constant, J/kg.K.
g= acceleration due to gravity (9.81), m/s^2.
H= enthalpy, J/kg.
h= heat transfer coefficient, $W/m^2 k$.
h_{fg}= latent heat, J/kg.
I= solar radiation intensity, W/m^2.

I_o = hourly extraterrestrial solar radiation intensity, W/m^2.

IR= irreversibility, W/m^2.

K= thermal conductivity, W/m.°k.

m= mass, kg.

$\dot{m}$ = productivity, kg/m^2.hr.

U= heat loss coefficient, W/m^2 °K.

v= average wind velocity, m/s.

W= work, J.

Greek Letters

α= absorptivity, dimensionless.

ε_w = water emissivity.

η= overall thermal efficiency, %.

τ= transmissivity, dimensionless.

Abbreviation

ETC= evacuated tube collector.

GI=galvanized iron.

TDS= total dissolved salts, mg/L.