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An Experimental Study to Improve the Performance of a Solar Still Using Solar Collectors and Heat Exchanger

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ABSTRACT

The performance of the double-slope solar distiller is combined with two types of solar collectors (vacuum tube solar heater ETC and solar concentrator PTC). The water inside the solar distiller is heated by a heat exchanger linked to the solar heater and the concentrator. 1.4, 1.7, and LPM 2). The results showed that the high temperature of the brine water inside the distillate was obtained at the LPM 2 flow, while the productivity was 2.248, 2.774, and 4.367 liters/day, respectively, for a depth of 0.05 meters of brackish water for the three flows, respectively. The maximum thermal efficiency capacity per hour was 53%. And 51% and 64.1% for the water flow of 1.4, 1.7, and LPM 2, respectively. 15.00 hours, the thermal efficiency per hour was maximum when the brine temperature was maximum, and the base of the tank was at 15.00 hours.

NOMENCLATURE

Latin Symbols:

Symbol	Description (Unit)
A_{ss}	Area of solar still (m2)
A_{etc}	Area of ETC (m2)
η_{ss}	Thermal efficiency (%)
m_{ew}	Hourly output of distilled water (l/h)
h_{fg}	Latent heat of evaporation at saline water temperature (kJ/kg)
G	Intensity of solar radiation of the solar still and ETC (W/ m2)
$\dot{V}_{prod}$	Productivity of solar still (ml)
W	Width (m)
L	Length (m)
$m\cdot$	Mass of saline water in solar still (kg)
cp	Specific heat of the air (kJ/kg K)
T_o	The temperature of the outer tube of ETC or PTC (°C)
T_{in}	The temperature of the inner tube of ETC or PTC (°C)
T_{amb}	The temperature of ambient (°C)
n_t	Number of tubes ETC
d_o	Diameter of the outer surface of the air tube (m)

List of Abbreviation

ETC	Evacuated Tube Collector.
PTC	parabolic Trough collector.
PCM	Phase Change Materials.

1. Introduction

Due to the significant and continuous increase in energy use, the energy crisis has become one of the world's most pressing issues today[1]. A limited supply of conventional energy, a significant increase in fuel prices, and environmental issues offset this. As a result of the problems produced by current energy sources, researchers have thought about developing new and alternative sources, with a focus on renewable energies[2]. Solar energy, as well as research and studies, have begun to address the fact that traditional fuels are dwindling and are being replaced by renewable energy[3]. Solar energy is the primary source of renewable energies on the surface of the earth that is sustainable, naturally generated, available in nature, inexhaustible, and limited at times, but always renewable and clean. It has no negative environmental impact when used with wind and water energy[4]. Tidal energy is formed through the gravitational forces between the earth, the moon, and the sun. It includes wave energy, the energy of temperature differences in ocean waters, and geothermal energy. Scientists define renewable energy as energy generated from the combustion of agricultural and household waste[5].

2. Solar Energy Technologies

Many solar energy technologies are integrated with solar stills to increase the device's efficiency. We mention some of them[6]:

i. Single-slope or double-slope solar collectors combined with flat-panel solar collectors.
ii. Single-slope or double-slope solar stills combined with evacuated tube solar heaters.
iii. Single-slope or double-slope solar stills combined with parabolic collectors.
iv. Tubular, pyramidal, and circular solar stills.

For single-slope or double-slope solar stills combined with flat solar collectors, [7] performed an experimental study on water desalination using a solar-powered solar distiller with phase change material integrated into a solar collector allowing continuous operation at night through a heat exchanger installed in the sump. Water was used to cool the outer surface with an optimal cooling water flow rate of approximately 10 ml/s. The results showed that the decrease in the water level led to an increase in productivity. The unit was capable of producing 4300 ml/m^2.day, about 40% of which comes after sunset. These units are only feasible in remote areas, according to economic analysis.

In the same application, [7] investigated the effect of combining a single-slope solar distillation with a high-frequency ultrasonic evaporator, PCM capsules, and an outdoor solar water heater on their performance in this study. In light of the difficult climate of Baghdad in the central region of Iraq, the results showed that PCM cylindrical capsules increased water productivity by 30.6%. The outdoor solar water heater and high-frequency ultrasonic evaporator increased water productivity by 41.5%, and the increased operating time of the ultrasonic evaporator had a negative impact on water productivity and thermal efficiency. Modified solar stills with an ultrasonic evaporator achieved a maximum thermal efficiency of 39.3% with a run time of 30 min and had a value of approximately 34.2% with a run time of 60 min. Expected costs of $0.037 and $0.028 per liter for standard and modified solar stills with an ultrasonic evaporator, straight.

[8] investigated the performance of a rotary solar wick (RWSS) under different operational and design conditions inside a distillation apparatus, a belt of black jute cloth was rotated vertically and horizontally. The effect of clockwise and counterclockwise filament belt sliding direction on RWSS performance was studied. The best performance of the RWSS was achieved at 0.05 m/s and in an up-down sliding direction. The RWSS freshwater yield outperformed the conventional solar distillation apparatus (CSS) by 300% and 260%, respectively, with and without reflectors. The thermal efficiency of RWSS and CSS was 82 with an average of 35%, respectively

For single-slope or double-slope solar stills combined with evacuated tube solar heaters, [9] studied conventional solar-powered distillers supported by four modified desalination technologies. The study was conducted under the climatic conditions of Alexandria, Egypt. The results showed that using a solar still with phase change material, and ultrasonic humidifiers combined with a vacuum solar still had maximum daily productivity of 5.34 and 7.4 kg per day for water depths of 25 and 35 ml, respectively. When used with a solar vacuum collector, the ultrasonic humidifier increased daily productivity by 25% and 44% at the same depths.

In a continuation of the same field, [10] studied the effect of incorporating a floating sponge layer on the performance of a stationary solar distiller (SSDU). Sponges were tested with different densities (16 to kg/m335) and thicknesses (0 to 40 ml) at different depths (10 to 40 ml) of saline water. The results show that using a sponge with a density of 316 kg/m^2, and a thickness of 30 ml at a depth of 10 ml in brackish water, the maximum daily freshwater production and thermal efficiency are recorded as 4.9 L/m2 per day and 37%, respectively, with corresponding increases of 58.1% and 55.3% When compared to traditional distillers, the cost of one litter of freshwater decreases by 35%.

Also, [11] compared the performance of graded solar still before and after modification based on the following evaluation criteria: the temperature difference between the brine and glass cover, evaporation/convection/radiative coefficients, the productivity of the solar still, and efficiency of the solar still. The daily productivity of the graded solar still increased by 29% after adjusting from 6.9 to 28.9 kg/m. Finally, the proposed graduated solar's thermal performance is still greatly improved with the new modification, based on the evaluation criteria and statistical test results. [12] examined the performance of a parabolic trough collector (PTC) coupled with a double-tilted solar ramp. Results show that stationary solar power with PTC has higher temperatures and higher productivity. At a brine level of 20 ml, the freshwater yield of solar stills with tracked PTC is 28.1% higher than that of a fixed PTC and approximately 142.3% higher than that of conventional solar collectors in summer and winter, solar stills coupled with fixed PTC yields about 28 kg/m .53 and 24.03 kg/m respectively per day. The daily efficiencies of conventional solar stills, fixed solar stills with fixed PTC, and fixed solar stills with tracking PTC are 36.87, 23.26, and 29.81%, respectively. The researcher [13] applied a new modified desalination technology to a conventional solar distillation machine to increase the distilled water yield for a single solar dish. According to the experimental results, the daily distillate productivity in the case of one solar dish was 8.8 and 5.45 kg/day at a water depth of 10 and 20 ml. Using two solar dishes with the solar distiller increases the daily productivity to 13.63 and 7.69 kg/day. At a water depth of 10 and 20 ml, respectively.

For research related to tubular, pyramidal, and circular solar stills, [14] conducted a study to improve the performance of tubular solar distillation, five different fixtures were used in it and under the distillation basin. The best case includes a V-shaped corrugated tub with filament, wt. 1.5%. CB Nano fluid and wt% 3% of CB nanoparticles were added to paraffin wax under distillation. For the cases with the previous sequence, the productivity increased by 21.4, 42.77, 58.48, 73.56, and 88.84%, respectively, compared with the conventional tubular solar shredder. [15] studied a hemispherical solar distiller with different metallic trays (copper, zinc, and iron) coated in black that were experimentally studied. The results showed that the cumulative yield of solar distillation was at L/m24.8 per day while using iron, zinc, and copper trays increased to 5.5, 6.3, and L/m27.35 per day, respectively. By 53.125%. CHSS, THSSI, THSSZ, and THSSC have thermal efficiencies of 37.4%, 42.8%, 49%, and 57.2%, respectively.

[16] the freshwater reserves on the earth are finite. The brackish water can be converted to fresh water by solar water distillery. The numerical analysis was carried out by using FORTRAN 90 program. The study considered several parameters: solar radiation intensity, ambient air temperature, ambient wind velocity, basin plate temperature, basin water temperature, glass cover temperature, and hollow cylinder surface temperature. The cumulative distillate water output from the modified solar still increased compared with the conventional solar still by a factor not less than 240%.

[17] this study is to be conducted to validate the optimum productivity of purification water by turning hollow-cylinder. Experimental results demonstrated that a basin water height is (1 cm) gives better productivity of (1225 ml/ m2.day) for conventional solar water distillation, and (2 cm) basin water height for the modification solar water distillation gives the optimum productivity, which is (3540 ml/m2.day) which represent an increase of 188% when compared with the productivity of the conventional solar water distillation. 0.5 rpm and 1rpm are the optimum rpm for the hollow cylinder for the modification solar water distillation without and with a flat plate solar water collector. The maximum percentage of productivity obtained from the modification solar water distillation, which is connected to a solar water heater with automatically varying speed according to the solar radiation intensity (Auto turning + Collector), gives more than (310%) enhancement. The estimated cost of one-liter distillate water output for modification and conventional solar water distilleries was 136 ID and 175 ID, respectively.

After reviewing the research related to improving the performance of the solar distiller through the use of several applications and linking it with it, we note that the impact of the researchers has conducted several studies on improving the performance of the distiller by using several types of solar collectors in addition to the use of concentrators in order to increase the productivity and efficiency of the solar distiller by increasing the temperature Water inside the distiller. Still, through follow-up research, the use of heat exchangers in this system has not been dealt with greatly, so we will do a study to improve the performance of the solar distiller by using a heat exchanger inside the distiller in order to increase productivity.

Therefore, the current work includes using a heat exchanger with a solar concentrator, a solar thermal heater, and a practical study of the system's overall performance.

3. Experimental work

The experimental system is located in a workshop in Kirkuk, Iraq (latitude o 35.4655 N and longitude o 44.38039 E). Kirkuk is a city with the sunniest days of the year; therefore, it is one of the favorite cities that can be chosen for solar energy experiments in terms of location.

A solar heater was designed and manufactured with a cylindrical solar collector of the parabolic type with two solar distillers, one of which contains a heat exchanger and is linked to the manhole, passing inside the first basin, while the other solar basin without any performance improvement.

3.1 Evacuated tube collector (ETC)

Figure (3-1a) shows a photograph of the tubular solar collector, as the solar heater used in this study consists of:

a. Evacuated tubes (ETC): their number is (36) evacuated tubes, the length of each tube is (180 cm), its external diameter is (58 mm), its internal diameter is (47 mm), and each tube contains 1.5 L of water, as shown in Figure (1).

b. The first tank contains 36 holes for inserting evacuated tubes into it, and the hole contains rubber to prevent water leakage from it. Another upper tank is smaller than it to preserve the water inside the first tank, as its length is (100 cm) and diameter is (31 cm).

3.2 Parabolic trough collector (PTC)

A cylindrical parabolic solar collector model was designed and manufactured locally with the technical specifications of the solar collector used in the research in terms of dimensions, its length (190 cm), width (100 cm), depth of the center (25 cm), the length of the mirror used (5 x 178 cm) and the length of the copper tube With the glass (176 cm) and the focal length (f) (25 cm), knowing that the tracking mechanism was manual, and the center was facing south, and the center's height from the ground was (110 cm) as shown in Figure (3-2).

3.3 Solar still (SS)

A solar still with a double-sloping glass cover was manufactured and connected with the solar collector system through a heat exchanger inside the still. The pilot solar distiller design consists of two parts:

a) Double-sloped glass cover.

b) The water basin: sheets of galvanized steel were used with a thickness of (mm 3) to be durable and light. The base area is (100 cm) long, (90 cm wide), and (20 cm high), and the length of the glass used is (100 cm) and (cm) wide. 55) The triangular glass has a height of (31.6 cm), and its inclination angle is 35 degrees from the horizon. As for the upper edges, they were bent horizontally with a width of (1 cm) at each end in order for the glass (transparent cover) to be fixed on it, but before placing the transparent glass cover and to ensure complete confinement of steam inside the still, and prevent its leakage to the outside, silicone material was placed on the bent edges Which work as a rubber gasket after its solidification, and then the glass cover was pasted on this gasket. The inner surface of the metal basin containing the water was coated with a black dye to increase the absorption of solar radiation and not reflect it outside the still. As for the thermal insulation, the distillates were completely isolated from the bottom and sides with a material (Sandwich panel). Figure () shows a photograph of the experimental system, and figure (1) shows the schematic diagram of the system. The supply pipe was connected to the basin from the side wall, while the drain line was considered at the other side wall of the basin. To control the water level inside the basin, where the water level (5 cm) was taken, the tank containing salt water feeds the distillers with salt water. We have inserted the float ball (the raft). . Channels were welded and installed on all sides of the solar distiller from four directions with an inclination of (5) degrees. To collect the distilled water that slipped from the transparent cover. As for the distilled water that slipped from the transparent cover, it is collected in the water collection channel inside the distiller, and it comes out of two openings on each side and comes out with an outlet. Thus, each distiller has two exits to produce distilled water on both sides of the distiller, where a rubber tube with a diameter of (ni 1) was placed. /2) and a length of (50 cm) on each outlet that enters the collection vessel to ensure that the steam generated is confined inside the distiller and that it does not leak from the outlet of the distilled water, and a valve was placed at the bottom of each distiller to empty the distilled water after the end of each test; To ensure the disposal of mud deposits and salts deposited inside the distillery. We used K-type thermocouples to measure the temperature of the basin, the water temperature, the steam temperature, the temperature of the glass cover, the temperature of the heat exchanger in the first basin connected to the solar collector, and the ambient temperature as shown in the Figure.\

The measurements were conducted for three different flow rates (1.4, 1.7, and 2 LPM), and the system was run from 8 Am until 5 PM on a sunny day in May. The temperature recording was taken depending on the thermocouples placed at different locations in the system; as seen from the figure(), the temperature sensors are placed on the inlet and outlet of the ETC, PTC, and heat exchanger inside the SS, on the external and internal glass wall, on the water surface, and finally on the basin surface at the bottom. A flow meter device was also placed on the flow line to measure the flow rate of the water. A Pyrometer device was placed to measure the solar intensity, and a device was used for reading wind speed and ambient temperature.

Fig. 1. Experiment set up of active solar still coupled with ETC and PTC.

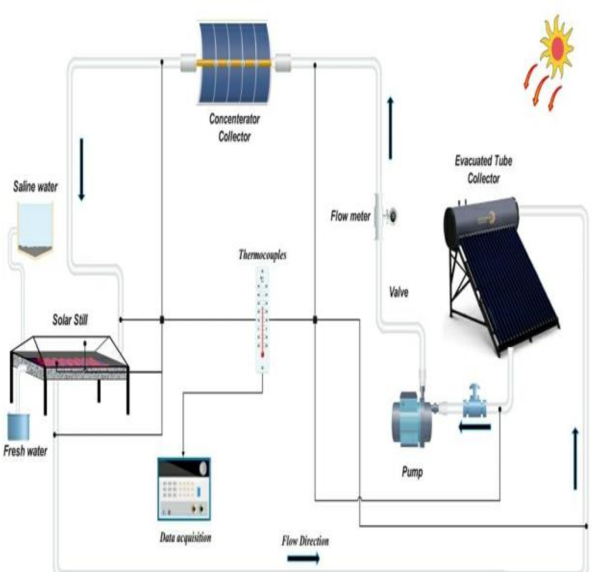

Fig. 2. Schematic diagram of solar still coupled with ETC and PTC

4. Mathematical model

The experimental system is located in a workshop in Kirkuk, Iraq (latitude o 35.4655 N and longitude o 44.38039 E). Kirkuk is a city with the sunniest days of the year; therefore, it is one of the favorite cities that can be chosen for solar energy experiments in terms of location.

4.1 Solar still model

We can calculate the efficiency of the solar still as follows[18][19]:

$$\eta_{ss} = \frac{m_{ew} \times h_{fg}}{G \times A_{ss}} \tag{1}$$

Where the water evaporation mass flow rate is calculated from collected fresh water per every hour and converted to (kg/s) of evaporated water as follows[20]:

$$m_{ew} = \frac{\dot{V}_{prod}}{3600} \tag{2}$$

Where $\dot{V}_{prod}$ the freshwater production in (L/h), and h_{fg} is the latent heat of the vaporization of water, which is obtained from thermodynamic tables. G is the solar intensity

$$A_{ss} = W \times L \tag{3}$$

Where W and L are the basin width and length, respectively.

4.2 Evacuated tube collector model

We can calculate the efficiency of the evacuated tube collector as follows[10] :

$$\eta_{etc} = \frac{Q_o}{Q_{in}} = \frac{\dot{m}\ cp\ (T_o - T_{in})}{G \times A_{etc}} \tag{4}$$

Where the water mass flow rate is obtained based on the flow rate of the pump and is calculated as follows:

$$\dot{m} = \frac{\dot{Q}}{60} \tag{5}$$

$$A_{etc} = \pi n_t d_o L \tag{6}$$

n_t is the number of tubes inside the ETC (36 tubes), d_o is the outer tube diameter of the ETC (3mm), and the length of the tubes is L which is around 1.8 meter. The outlet and inlet temperature from the ETC is T_o and T_{in}, respectively.

5. Results

Results from the two types of solar stills under study—conventional and developed—were obtained using evacuated tube collectors, parabolic trough collectors, and packed beds.

5.1 ETC and PTC results

Figures (3, 4, and 5) show the variation of the sun's intensity and temperature in prominent

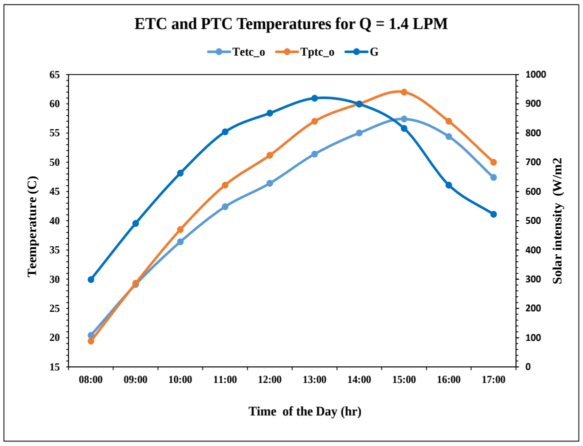

Fig. 3. Variation of solar intensity and the outlet temperatures of ETC and PTC, respectively, with respect to time at 27/5/2022

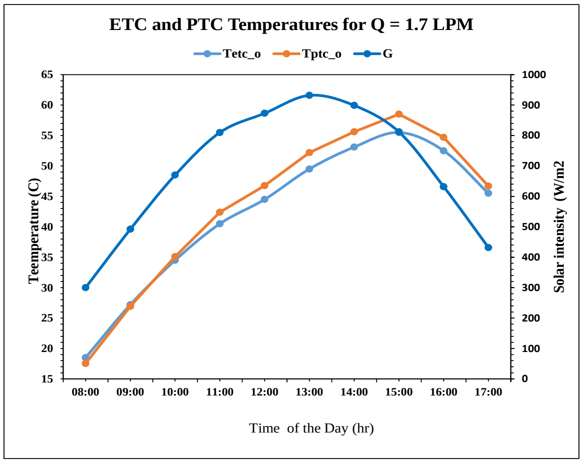

Fig.4 Variation of solar intensity and the outlet temperatures of ETC and PTC respectively with respect to time at 28/5/2022

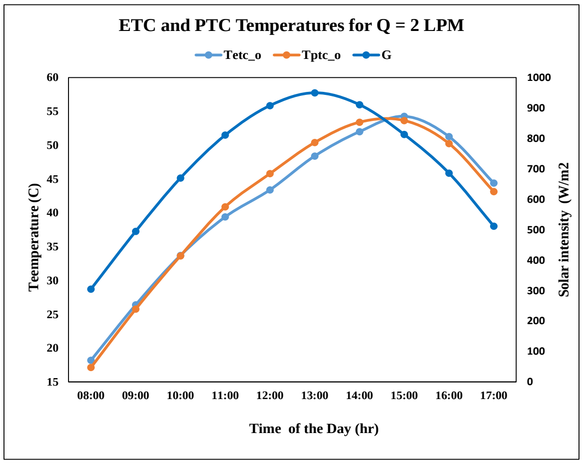

Fig.5. Variation of solar intensity and the outlet temperatures of ETC and PTC, respectively, with respect to time at 29/5/2022

locations with respect to the time from 08.00 to 17.00 hours on 27, 28, 29/5/2022. At the beginning of the experiment, at q = 1.4, 1.7, and 2 LPM, the chart showed the measured and exit temperatures of the ETC and PTC, respectively. Solar noon in May was regulated at 1 pm in the tested area. Moreover, the external temperature of the solar heater at the lowest speed of the pump with flow showed 1.4 LPM higher than the flow 1.7 and 2 LPM, respectively, because the water stays longer in the heater and heats up, and this also helps in the center to stay longer in the tube to hit the concentrated solar radiation for a while of time, and thus we obtain the highest temperature of hot water at 15:00 hours, reaching in flows 1.4, 1.7, and 2 LPM to 57.7°C, 55.5°C, and 54.2°C for ETC This corresponds to the behavior of the outside temperatures at the researcher[22], 62°C, 58.5°C, and 53.6°C for PTC, respectively This corresponds to the behavior of the outside temperatures at the researcher [14], so we note that the flow The first (1.4 LPM) the difference between the exit of the heater and the exit of the center is very clear, while they converge at the second and third flows, and this appears in the temperatures from early morning until 3 pm before they decrease with the passage of time.

5.2 Solar still results

A comprehensive understanding of the still's performance can only be obtained by measuring the temperature at various locations. Figure (6, 7, 8) shows the variation of the sun's intensity and temperature in prominent locations with respect to the time from 08.00 to 17.00 hours on 27, 28, 29/5/2022. At the beginning of the experiment at q = 1.4, 1.7, and 2 LPM, respectively, the chart showed the measured temperatures of the inner glass cover (Tg -in), the outer glass cover (Tg-out), the temperature of the basin base (Tb) and the ambient temperature (Tamb) of the solar energy. Conventional with solar intensity, respectively. The solar noon in May was regulated at 1 pm in the tested area.

Furthermore, it showed that the inner and outer glass temperature of the outer glass cover (Tg-out) was close to the ambient temperature (tamb) that d the difference between the two temperatures gradually increased. Because of the thermal mass of the water, there was a time difference of 2 to 3 hours between the maximum insolation and the maximum temperature of the salt water. The temperature of the outer glass at its highest value was 61.3 ° C, the temperature of the basin base was 62.7 ° C, and the temperature of the water at its exit from the exchanger was 64 ° C. An increase in temperature from early morning until 3 pm before it decreased over time. This corresponds to the behavior of the outside temperatures at the researcher[23][24].

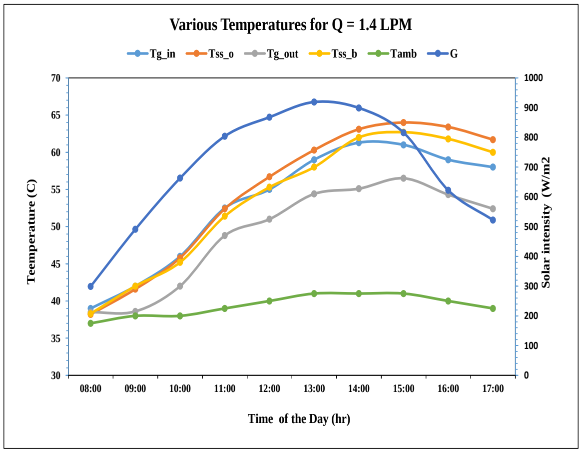

Fig. 6. Variation of solar intensity and the temperatures with respect to time for active solar still coupled with ETC and PTC, respectively, at 27/5/2022

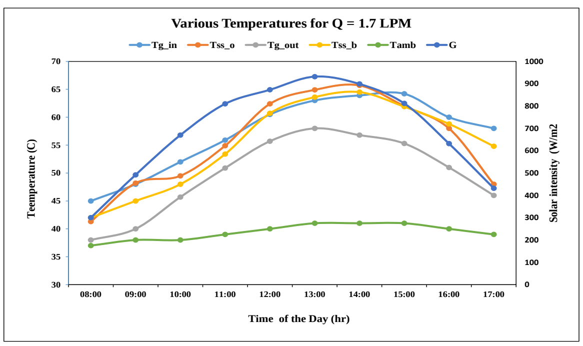

Fig. 7. Variation of solar intensity and the temperatures with respect to time for active solar still coupled with ETC and ptc, respectively, at 29/5/2022

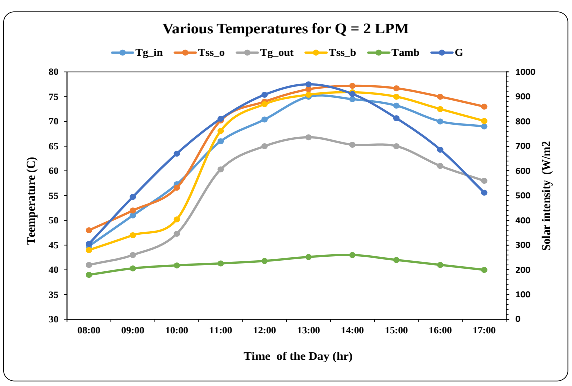

Fig.8. Variation of solar intensity and the temperatures with respect to time for active solar still coupled with ETC and PTC, respectively, at 29/5/2022.

Figure (9) shows the experimentally measured variance in the daily hourly yield with respect to time for different flows of water within the exchanger on 27, 28, 29/5/2022. The daily yield recorded for q = 1.4 LPM, q = 1.7 LPM, and q = 2 LPM was 2.248 ml/hr, 2.774 ml/hr, and 4.367 ml/hr, respectively. The maximum hourly productivity was 0.588, 0.639 ml/hr, and 0.9 ml/hr for 0.05 m depth of brackish water, respectively [25].

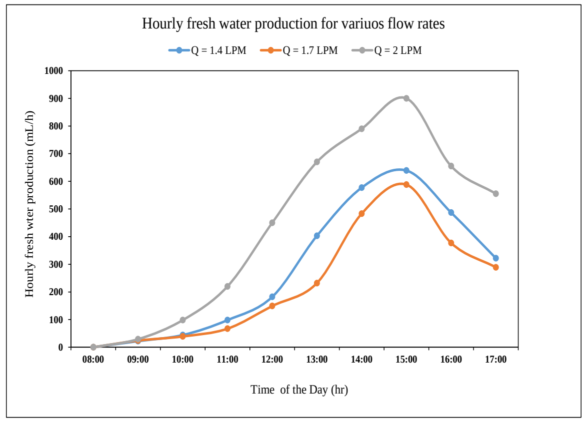

Fig. 9. Hourly freshwater production variation with respect to time for various flow rates.

Figure 10 expresses the variance of experimentally achieved hourly thermal efficiency with respect to time from 8.00 to 17.00 hours for water flows of 1.4, 1.7, and 2 LPM, respectively. The maximum hourly thermal efficiency has been estimated to be 53%, 51%, and 64.1% for water flows of 1.4, 1.7, and 2 LPM, respectively, for a saline depth of 0.05 m. 15.00 hours, the thermal efficiency per hour was maximum when the brine temperature was maximum, and the base of the tank was at 15.00 hours[26].

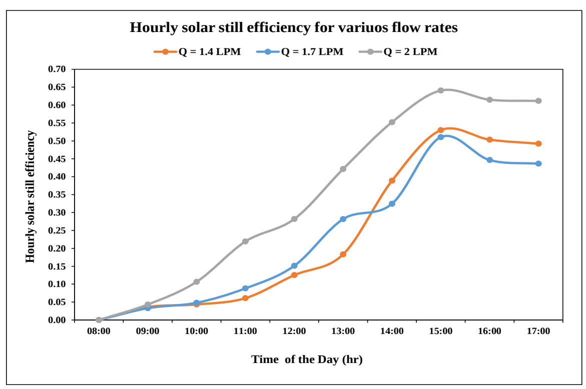

Fig. 10. Hourly thermal efficiency variation with respect to time for various flow rates.

6. Conclusion

The performance of the solar distiller with a double slope, with a water depth of 0.05 m. inside it is a heat exchanger to heat the water inside the solar distiller, with the help of the heater and the concentrator, which heat the water by solar radiation. A three-speed pump with different flows (1.4, 1.7, and 2 LPM) was used. The results showed that the external temperature of the solar heater at the lowest speed of the pump with a flow of 1.4 LPM is higher than the flow of 1.7 and 2 LPM, respectively, because the water stays longer in the heater and heats up, and this also helps in the center to stay longer in the tube to hit the concentrated solar radiation for a period of time Thus, we obtain the highest temperature of hot water at 15:00, reaching in flows 1.4, 1.7, and 2 LPM to 57.7°C, 55.5°C, and 54.2°C for ETC, 62°C, 58.5°C, and 53.6°C for PTC, respectively, while in the solar distiller it showed The temperature of the inner and outer glass The temperature of the outer glass cover (Tgo) was close to the ambient temperature (tamb) and the difference between the two temperatures increased gradually and the temperature was high for the salt water at the 2 LPM flow because when the flow increased it led to an increase in the water temperature The salt inside the distillate, thus increasing the evaporation process and due to the thermal mass of the water, there was a time difference of 2 to 3 hours between the maximum insolation and the maximum temperature of the salty water. The temperature of the outer glass at its highest value was 61.3 °C, the temperature of the basin base was 62.7 °C, and the temperature of the water at its exit from the exchanger was 64 °C. The maximum thermal efficiency capacity for the hour was 53%, 51%, and 64.1% for the flows waters of 1.4, 1.7, and 2 LPM, respectively, for a saline depth of 0.05 m. 15.00 hours, the thermal efficiency per hour was maximum when the brine temperature was maximum, and the basin base was at 15.00 hours. While the productivity was 2.248 ml/hr, 2.774 ml/hr, and 4.367 ml/hr, respectively. The maximum productivity per hour was 0.588 ml/hr, 0.639 ml/hr, and 0.9 ml/hr for a depth of 0.05 meters of brackish water for the three flows, respectively. Solar productivity is still affected by environmental factors such as wind, ambient temperature, and solar radiation intensity. The wind affects the glass, and it cools, thus facilitating the condensation process, thus increasing the distilled productivity[27].

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