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Experimental Investigation of the Effect of Evacuated Tubes and Glass Cover Cooling on the Performance of the Solar Still

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ABSTRACT

Solar distillation has gained more importance as a practical and environmentally friendly solution for converting non-potable water into clean water using solar energy, in response to the increasing concern about the scarcity of clean water. In the city of Kirkuk, Iraq, located at 35.4666° N, 44.3799° E, we conducted an experiment to enhance the efficiency of a conventional solar distiller with a surface area of 1 m^2. To enhance evaporation, we incorporated 8 vacuum tubes. For improved condensation, we conducted experiments using two different cooling methods to cool the glass cover: pulse cooling (1min/15min), (1min/10min) and continuous cooling. Based on the trial findings, the productivity reached 2653 ml/day, representing a 237.5% increase in production. When vacuum tubes were attached to the solar still, the productivity increased compared to a conventional distiller. With a cooling time of (1min/15min), the productivity reached 3510 ml/day. With a cooling(1min/10min), the productivity reached 3587ml/day. When constantly cooling, the productivity reached 4980 ml/day. The productivity experienced respective increases of 332%, 386%, and 656.8% in comparison to the conventional distiller. The modified still's thermal efficiency was 21.6%, 24.6%, and 37.7%, compared to 17% for the conventional system and 18.8% for the improved system without glass cover cooling.

1. INTRODUCTION

Approximately 99% of the water on Earth is either salty or brackish, and just 1% is considered fresh. Even if there is a lot of saltwater available, it takes a lot of work to purify it. One of the greatest challenges of the 21st century is figuring out how to make water purification technology more effective and efficient so that we can have access to clean water while also reducing our long-term impact on the environment [1]. There is a critical lack of potable water, and only one-third of the world's population has access to it. Infections and infectious illnesses may spread more easily when people do not have access to clean water. Therefore, it is essential to supply isolated and dry locations with long-term supplies of drinkable water [2, 3]. Consumers should avoid drinking water with a total dissolved solids (TDS) level greater than 1000 mg/l. A TDS level below 600 mg/l is typically regarded as good. There is no recommended health value recommendation and no credible evidence on the possible health impacts of TDS consumption in drinking water [4].

Fuel, the world's principal energy source, powers most desalination techniques. The usage and reserves of fossil fuels are limited, and the environment is dirty. To solve fossil fuel dependence through renewable energy, researchers and governments are persistently developing it. Viable, pollutant-free, plentiful, and sustainable [5].

Solar energy is widely recognized as a very viable and practical source of energy within the realm of sustainable energy options. The Earth has a substantial quantity of it, with its size varying regionally. It is used in many applications, such as air heating, water heating, solar cooking, sun drying, power production, and solar distillation [6].

Solar distillation is a common desalination method because it is both cost-effective and energy-efficient. Is the best option to minimize environmental issues and be sustainable [7]. Throughout its lifetime, the solar still lessens emissions of nitrogen oxide, sulfur dioxide, and carbon dioxide into the environment [8]. A solar distiller is an apparatus. Its solar energy is used to desalinate dirty or brackish water. The system of water purification uses solar radiation to supply potable water for industrial, agricultural, and domestic purposes [9, 10]. The simplest distiller, the passive solar still, relies on meteorological factors including solar radiation intensity, air temperature, relative humidity, wind speed, and design characteristics like water depth, insulation, and basin liner absorbency. Area latitude must match glass cover inclination. Low productivity and thermal efficiency are its key drawbacks [11, 12].

Solar stills' limited production is its biggest problem. Researchers have developed several strategies to boost evaporation and condensation. Evaporation is increased using evacuated tube collectors, nanofluid, energy-storing materials, wicks, reflecting mirrors, and parabolic through collectors. Cooling the glass cover increases condensation [13].

Integrating the double basin solar still with an FPC and a solar pond produces a 127.65% increase in output [14]. Adding a parabolic through collector to the single slope solar still raised the water temperature in the still basin, increasing production by 4.1 L/m^2 at 5 cm depth [15].

Theoretical studies of solar still connected to ETC showed that it could theoretically treat fresh water scarcity in remote and solar-rich areas in a sustainable way, with a daily production of 3.8 liters/m^2 and an annual dilution of 77.2 tons of carbon [16]. Connecting the solar still to the ETC with a heat pipe increased the temperature differential between the water in the basin of the still and the glass cover 30 percent and output by 62 percent [17]. A solar distiller produces 1.72 kg/m^2 and improves efficiency by 63.8% in a stepped basin solar still with ETC and a compound parabolic concentrator [18].

With water flowing over the glass cover of the hybrid solar still system, thermal efficiency rises by 4% and daily exercise output by 8.2% [19]. Solar stills that use water for cooling are 81.1% more productive than those that use air. The production cost of water for solar stills cooled by water is 0.243$/L, whereas for stills cooled by air it is 0.277$/L [20]. Using pulsed cooling over the glass cover of a solar distiller results in a 36.7% increase in production compared to continuous cooling, which only yields a 10% increase in output [21].

According to the previews research, solar stills that are linked to evacuated tubes enhance efficiency and provide realistic options to improve water production in regions experiencing significant water scarcity. Nevertheless, there has been no investigation of a solar still that is linked to evacuated tubes directly.

This study aims to improve the efficiency of a solar distiller through two modifications: increasing the water evaporation within the still receptacle by directly incorporating vacuum solar tubes, and increasing condensation by regularly cooling the glass cover. in the climatic conditions in Kirkuk City, Iraq (35.4666° N, 44.3799° E).

2. EXPERIMANTAL SETUP

The system consists of two single slope solar stills constructed in the city of Kirkuk, Iraq, at coordinates (latitude: 35.4686, longitude: 44.38933). The experiments were carried out in November and December, with two solar still oriented towards the south [22], as shown in Figure 1. The original and enhanced stills are constructed with a square base of 1 m², composed of galvanized iron with a 2-millimeter thickness. It is characterized by its durability, accessibility, and affordability. Additionally, it is coated internally with matte black paint. To enhance solar radiation absorption and subsequently raise the water temperature, the system incorporates a floating platform to regulate the water level inside the basin as well as a channel set at a 5° angle to promote the flow of distilled water into the collecting container. The distiller is asymmetrical, with a front height of 15cm and a rear height of 85cm, and it is at an angle of 35° incline, the same as the latitude in Kirkuk. Glass has a 4 mm thickness and a 0.76 watt/m K thermal conductivity. It is equipped with a silicone rubber substance to ensure the prevention of steam leakage. The bottom and sides are insulated with a 12 mm-thick layer of Armaflex to minimize heat loss [23, 24]. The sole means of heating the water with solar energy it gets through a glass cover. Water within the conventional distiller. To enhance the distiller, it features a slightly inclined bottom section that is linked to 8 vacuum tubes, facilitating a flow of water to and from the solar distiller. The object is positioned at an inclination of 50° relative to the horizon. The tube has a length 150 cm, a 47 mm outer diameter, and a 34 mm interior diameter. There is a gap between them that helps minimize the amount of heat loss. To lower the temperature of a glass cover, we employ a perforated tube. The water is contained within a cork tank equipped with a water pump that operates at a flow rate of 1400 L/hr. Additionally, there is a separate tank to supply water to the distillers, and the connecting tubes are constructed of thermally insulated rubber. The experimental setup dimensions are shown in Table 1.

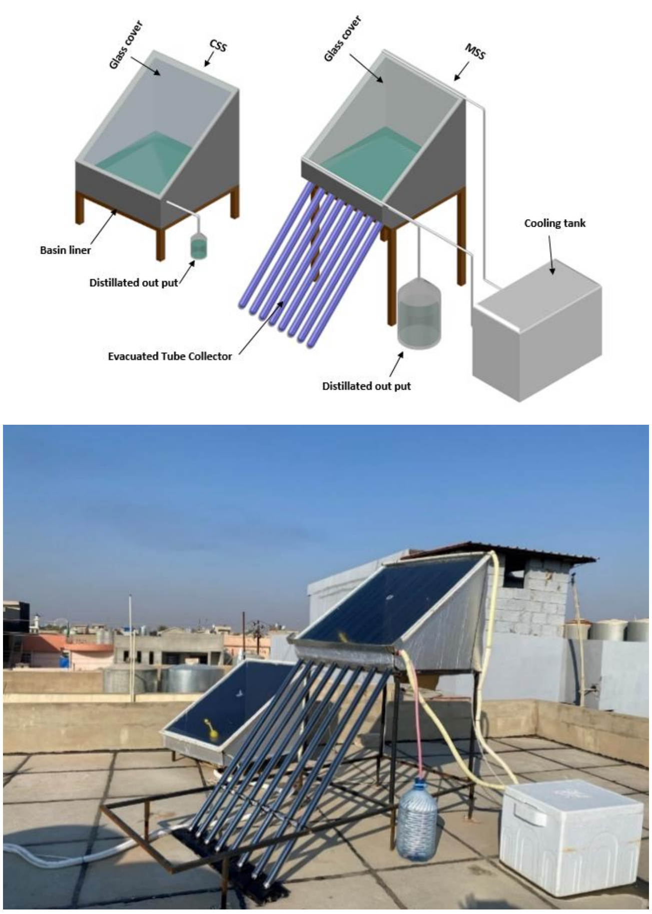

Figure 1. Experimental set up of CSS and MSS

A solar power meter is used to measure solar radiation with a range of (1-3999) watt/m^2 and an accuracy of (± 10) watt/m^2. A digital anemometer is used to measure wind velocity. It has a range of (0-45) m/s and an accuracy of (±3%). The temperature is recorded using a T-type thermocouple with a range of (-250 to 350) ℃ and a data logger with an accuracy of (± 10) ℃. A plastic jar is used to measure the output of distilled water. It has a range of (0-2000) ml and an accuracy of (± 5) ml. Digital Thermo Hygrometer to measure relative humidity and temperature in the atmosphere, Accuracy (±1) ℃. To control the water pump in the intermittent cooling system that cools the glass cover, use a time-relay device. time-adjustable range: 0.1 sec-99 hr.

Table 1. Dimensions of experimental set up

Parameters	Value
Area of passive and active solar stills	1 m^2
Inclination angle of the glass cover	35º
Thickness of the glass cover	4 mm
Thermal conductivity of glass cover	0.76 w/m k
Absorber plate material	Galvanized iron (2 mm thickness)
Thermal conductivity of absorber plate	73 w/m k
Basin and wall insulation	Armaflex (12 mm thickness)
Coating of basins	Industrial matt black
Sealant	Thermal silicon
Number of evacuated tube collectors	8
Length	1.5 m
Outer diameter of the evacuated tube	47 mm
Inner diameter of an evacuated tube	34 mm
Thickness of glass of each evacuated tube	1.6 mm
Glass material of an evacuated tube	Borosilicate glass 3.3
Coating absorbs	Al-N/Al graded
Inclination of evacuated tube	50º
Water pump	1400 L/h

3. WORKING AND PROCEDURE OF THE EXPERIMENT

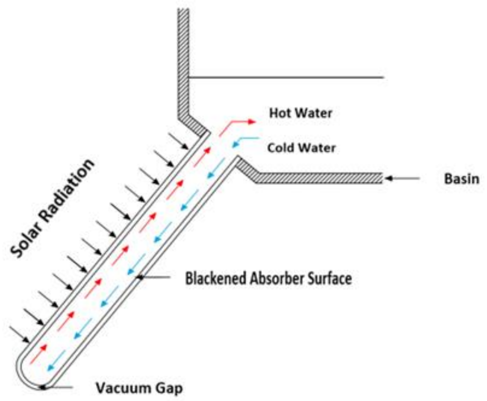

Figure 2. A schematic diagram of the thermosyphon process between ETC and solar still

As a pre-experiment step, we dust out the evacuated tubes and the solar still's glass cover. Next, we fill up the conventional still's basin with water from the tank and transfer it to the distillers' basin via connecting pipes. The enhanced distiller works by filling the basin and tubes with water. Both stills have a water depth of 5 cm. The vacuum tubes heat the water, and the collector absorbs the heat. Solar energy is used to heat water in evacuated tubes. Natural circulation causes hot water to ascend in a solar collector and into a basin, forcing the cold water at the basin to drain and return to the collector for further heating. Figure 2 illustrates this process. So, the water in a still evaporates, and the vapor rises to the cover. As water condenses inside a glass cover, it falls into the stream and eventually collects in the collecting vessel as a result of gravity. Water sprinklers cool the glass cover to enhance water vapor condensation, and we link the water pump to the time relay for pulse cooling. Temperatures are measured using a T-type thermocouple in eight places: Temperature of the water in the tank feeding the distillers, inner surface of the glass cover, surfaces of water and the base of basin in both distillers, and the temperature of the cold water installed with a data logger. We measure the intensity of solar radiation, air temperature, wind speed, and relative humidity in the atmosphere every hour from 8 a.m. to 8 p.m. in November and December.

4. SOLAR STILL EFFICIENCY

Solar distiller efficiency is a significant indicator for evaluating a performance of both passive and active solar distillation systems. The expression "efficiency" refers to the amount of energy used for water evaporation within the still relative to the solar energy that enters the system. A passive solar distiller's thermal efficiency is estimated as [25]:

$$\eta_{passive} = \frac{m_{ew} \times L}{(I(t)_s \times A_s \times 3600)} \tag{1}$$

An active solar distiller is estimated as:

$$\eta_{active} = \frac{m_{ew} \times L}{((\mathrm{I}(t)_c \times A_c \times 3600) + (I(t)_s \times A_s \times 3600))} \tag{2}$$

According to the results of the Eqs. (1) and (2) in Figure 3, the passive distiller had a thermal efficiency of 17%, the active distiller linked to vacuum tubes without cooling the glass cover had a thermal efficiency of 18.8%, the active distiller with pulse cooling (1 min/15 min) had a thermal efficiency of 21.6%, and the active distiller with pulse cooling (1 min/10 min) had a complete efficiency of 24.6%; the maximum thermal efficiency was 37.7% when the active distiller was continually cooled.

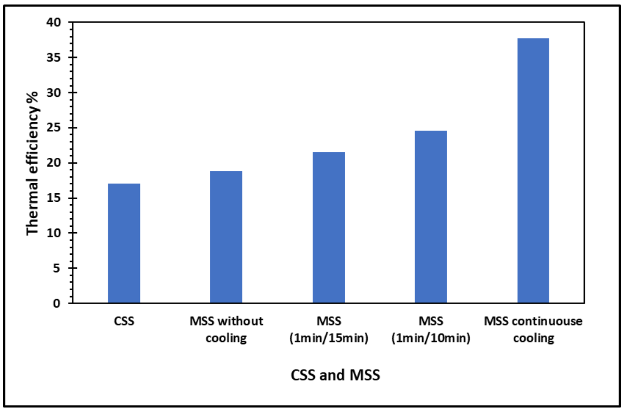

Figure 3. Thermal efficiency of CSS and MSS

5. RESULTS AND DISCUSSION

This present study incorporates both conventional and enhanced distillers; the first type does not use any additives, while the latter incorporates two enhancements. One enhancement would be to link the vacuum tubes directly to solar still; this would raise the temperature of the water in the basin, speeding up evaporation process and allowing it to remain at a high temperature long after sunset, thus increasing output. Increasing the condensation process by spraying the water on the glass cover is the second enhancement. Additional elements that impact the output on a daily basis include.

5.1 Effects of ambient temperature and solar intensity on solar stills

The ambient temperature and the intensity of solar radiation are two environmental variables that affect the solar still's output [26]. Radiation from the sun reaches its peak at 12 p.m., reaching 650 W/m^2 on the still's surface and 1150 W/m^2 on the evacuated tubes' surface, as seen in Figure 4. With a low of 14.7℃ at 8 a.m. and a high of 19.8℃ at 3 p.m., solar radiation and ambient temperature start decreasing gradually until sunset. According to the time in Kirkuk, Iraq, on November 30, 2023.

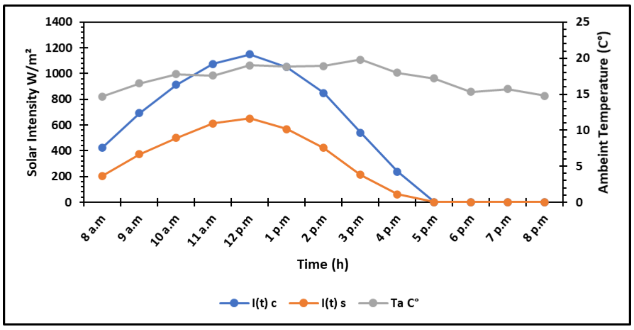

Figure 4. Hourly variation of ambient temperature and solar intensity

5.2 Effects of wind velocity and relative humidity on the solar stills

Climatic variables such as wind velocity and relative humidity have a direct effect on the efficiency of the solar still. Through reducing the temperature of the glass cover, these factors enable a condensation process, which in the end enhances the still's productivity [2]. The wind speed and relative humidity from 8:00 a.m. to 8:00 p.m. are depicted in Figure 5.

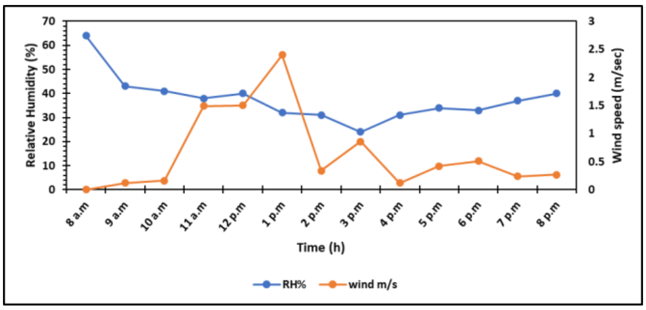

Figure 5. Variation of wind velocity and relative humidity in 1/12/2023

5.3 Effects of adding ETC to a solar still

The temperature of the water in the basin is an important yield factor. Adding evacuated tubes to a solar still raises the temperature of the water [27]. During the day, solar radiation raises the temperature of the water inside the evacuated tubes, causing cold water to flow down and become warm. This warm water then mixes with cold water in the basin reservoir and flows to the evacuated tubes, repeating the cycle. Natural circulation, as seen in Figure 2, and the tube's vacuum insulates and decreases heat loss to the atmosphere. The productivity of the modified distillate was 2653 ml, and the conventional one was 786 ml, increasing production by 237.5% over a conventional still. Figure 6 shows the variation of hourly productivity in CSS and MSS. Figure 7 shows daily productivity in CSS and MSS.

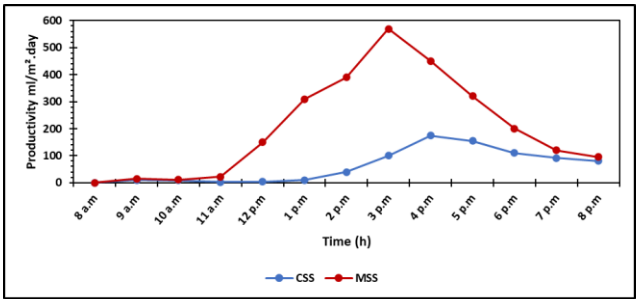

Figure 6. Variation of hourly productivity in CSS and MSS in 1/12/2023

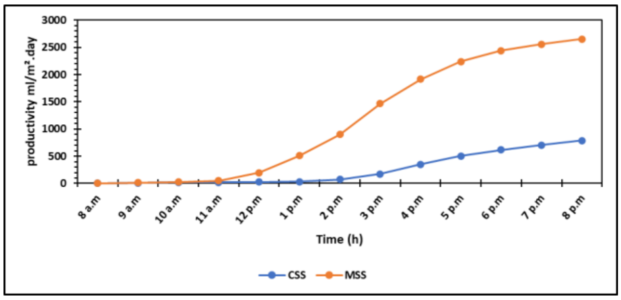

Figure 7. Daily productivity of CSS and MSS with ETC in 1/12/2023

5.4 Effects of a cooling glass cover on a solar still

One of the primary variables influencing production is the temperature differential between water's surface and a glass cover. The condensation rate and, by extension, productivity rise in direct proportion to the amount of the temperature gradient. We tried various methods to cool the glass cover, such as pulsed cooling and continuous cooling. Figure 8 shows the productivity of the conventional still increased by 332% to 3510 ml/day when the cover was cooled by pulse spraying for 1 minute every 15 minutes on November 24, 2023. On November 30, 2023, the productivity further increased by 386% to 3587 ml/day when the cooling was done for 1 minute every 10 minutes. Finally, on December 8, 2023, the productivity reached 4970 ml/day, an increase of 656.8% when continuous cooling was implemented, and it reached a maximum of 4980 ml. Consequently, we inferred that reducing waiting time increases production.

As shown in Figure 9, the present study found that the improved distiller connected to evacuated tubes can be continuously cooled to increase productivity by 656.8% compared to the conventional still and by 87.7% compared to the improved still connected to evacuated tubes without cooling the glass cover. Figure 10 shows hourly productivity in CSS and MSS. The study conducted an analysis of the overall productivity of modified and conventional stills in Kirkuk, Iraq, for the months of November and December 2023. As shown in Figure 11. The Figure 12 shows compressive productivity with other researchers.

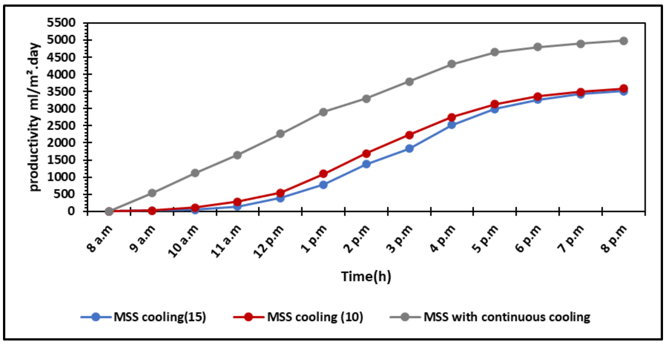

Figure 8. Cumulative productivity of different type cooling glass cover mechanisms 1) MSS with (1 min/15 min), 2) MSS with (1 min/10 min), MSS continues spray cooling

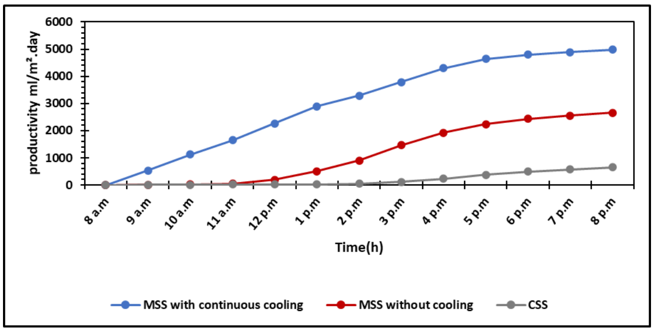

Figure 9. Cumulative productivity of CSS, MSS without cooling in 1/12/2023, MSS with continuous cooling in 8/12/2023

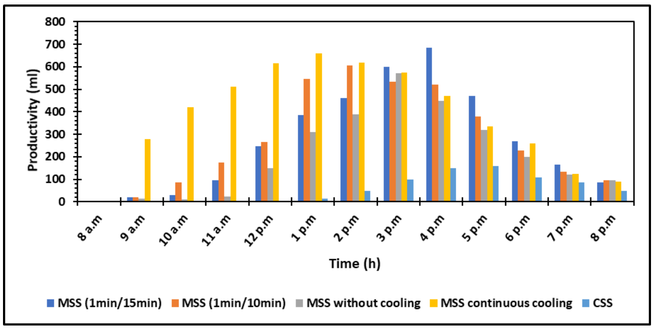

Figure 10. Hourly productivity of CSS and MSS

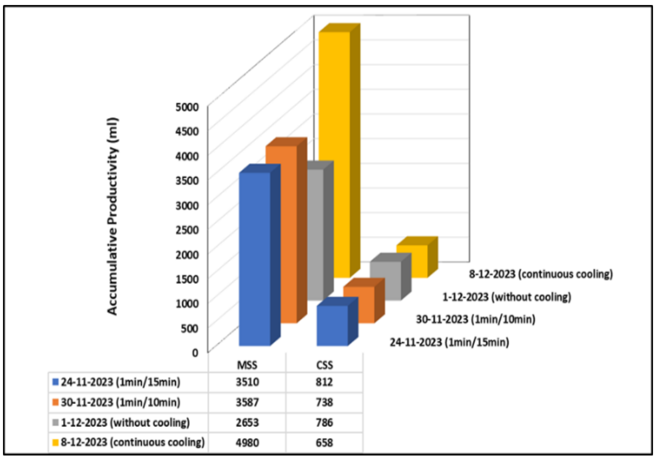

Figure 11. Comparison of modified and conventional still output in Kirkuk, Iraq, for November and December 2023

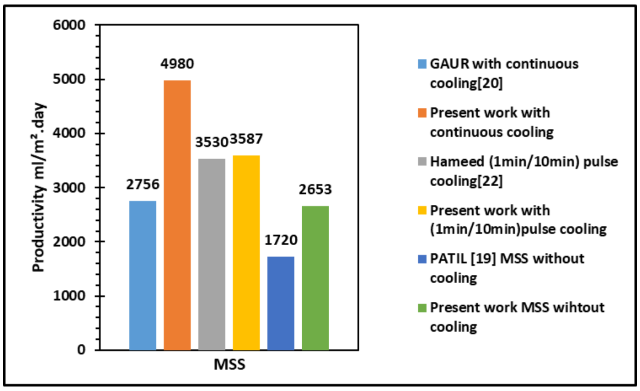

Figure 12. Compressive productivity with other researchers

6. THE ECONOMIC FEASIBILITY OF SOLAR STILL

According to the data in the Table 2, the fixed cost of a conventional solar still is around \$94. Using the following formula, we can determine the average manufacturing costs of one liter of distilled water [28]:

$$Y = F + X$$

(Y) = final cost
(F) = Fixed cost = 94 \$
(X) = Maintenance and operation cost = 94 × 0.3 × 20

$$Y = 94 + (94 \times 0.3 \times 20) = 658$$
$$658/4568.9 = 0.144\ \$$$

(F) It stands for the solar still's fixed cost; (X) is that fixed cost multiplied by 0.3 and the number of bright days in Kirkuk city, which is estimated at 305 days over 20 years; this yields the final cost of the traditional still, which is \$658. For a conventional distiller, the typical daily output is 0.749 liters times 305 sunny days over a 20-year period. Over the course of 20 years, the typical output is 4568.9 liters. The production cost of one liter of distilled water is 0.144 dollars, calculated by dividing 658 by 4568.9.

Table 2 shows that the improved still has a fixed cost of \$205 and a monthly production rate of 3.683 liters. Over a 20-year period, the average productivity in Kirkuk, Iraq, under the climatic conditions of 305 sunny days per year, is 22,466.3 liters. Using the following formula, we can determine how much the improved distiller will cost per liter of water:

$$Y = F + X$$
$$Y = 205 + (205 \times 0.3 \times 20) = 1435$$
$$1435/22466.3 = 0.064\$$$

Table 2. The fixed material costs (\$) for both conventional and modified solar stills

Material	MSS	CSS
Galvanized iron	57	57
Glass cover	6	6
Insulation	16	16
ETC	100	-
Water pump	5	-
Time relay	6	-
Plastic pipe	2	2
Paint	3	3
Other	10	10
The total cost	205\$	94\$

7. CONCLUSIONS

In the present experiment, we performed an experimental analysis to estimate the performance of a solar distiller combined with vacuum tubes and glass cover cooling in the climatic conditions of Kirkuk, Iraq. We compared its productivity with that of a conventional solar distiller based on experiments conducted with different parameters:

- During the day, the ambient temperature and intensity of solar radiation rise, increasing solar still productivity. Productivity increases when wind speeds cool the glass cover.
- The integration of vacuum tubes with the solar still resulted in 2653 ml/day, a 237.5% enhance in productivity when compared to a conventional solar distiller.
- A pulse cooling system with a 1-minute on, 15-minutes off cycle on the modified solar distiller's glass cover increased production by 332% to 3510 ml per day. Pulse cooling for 1 minute every 10 minutes increased production by 386% to 3587 ml/day.
- The implementation of continuous cooling in the modified solar still resulted in a significant increase of 656.8%, with a maximum output of 4980 ml/day. Therefore, decreasing the amount of time spent waiting leads to an enhance in production.
- The thermal efficiency in conventional solar stills is 17%, while the modified solar distiller with vacuum tubes is 18.8%, pulse cooling (1 min/15 min) is 21.6%, and pulse cooling (1 min/10 min) is 24.6%. The maximum thermal efficiency was 37.7% when continuously cooled.

Some of the future recommendations that may be gleaned from the results are:

1. Attach 10 pipes directly to the solar still to enhance the rate of water evaporation throughout the autumn and winter seasons.
2. using varying concentrations of nanomaterials within the basin of the still to enhance the rate of water evaporation.
3. Conduct studies on cloudy days and compare their productivity to that of sunny days.
4. Enhance condensation by utilizing a double-layered glass system instead of a single-layered one with air circulation in between.
5. Reuse the experiments in the spring and continuously cooling the glass cover to increase the rate of vapor condensation.

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NOMENCLATURE

A_C	surface area of ETC, m^2
As	surface area basin, m^2
$I(t)_c$	intensity of solar radiation on ETC, W/m^2
$I(t)_s$	intensity of solar radiation on solar still, W/m^2
L	latent heat of vaporization, J/kg
m_{ew}	hourly distillate output, Kg/m^2

Abbreviation

CSS	conventional solar still
ETC	evacuated tube collectors
MSS	modify solar still
TDS	total dissolved solids