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Performance comparison of solar stills using two kinds of solar collectors

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ABSTRACT

This study presents a practical investigation of the effect of two different solar collectors (parabolic concentrator collector and evacuated cylindrical collector) on the solar distiller performance. The experiments were carried out under the climatic conditions of the Iraqi city of Kirkuk (35.46°N, 44.39°E). The results of the testing showed that adding solar collectors raised the temperature of the basin water for the solar distiller. The water in the distiller basin connected to the parabolic concentrator collector reached a maximum temperature of about 71°C. In contrast, the water temperature of the traditional distiller was 67°C. Also, the findings exposed that connecting the conventional solar distiller with different kinds of solar collectors has no significant benefit in enhancing the output of solar distillers. The maximum water production of the solar distiller connected with a parabolic concentrator collector was 1.38 E-04 L/s at 3 p.m. It was also noted that the hybrid solar distillers have higher productivity than the traditional distillers after 3:00 p.m. At a volume flow rate of 1.4 L/min, the daily thermal efficiency of the distiller integrated with the parabolic concentrator collector, the distiller integrated with the evacuated cylindrical collector, and the classical distiller was 27%, 23.64%, and 34.44%, respectively. The results also showed that the solar distiller coupled to an evacuated solar collector operates more efficiently with a higher cooling water flow rate.

Keywords: Solar distiller; Performance; Integrated; Solar collectors

1. Introduction

The lack of energy supply is one of the great challenges opposite humanity owed to experts' warnings about fuel depletion and the environmental problems associated with its use [1,2]. Scientists have paid great attention to renewable energies, especially solar energy, to address the problem of depletion of traditional fuels and to reduce global environmental pollution [3]. The uses of solar energy have varied at present, and there are various solar energy systems such as solar collectors, PV panels [4], solar distillers [5], solar chimneys, solar ponds, solar drying, Trombe wall, and others. The increase in the global population and the rise in economic and human activity resulted in a notable intensification in the consumption of fresh water, which required searching for means to desalinate salt water [6]. Therefore, providing usable water will be one of humanity's most critical problems [7]. In many countries, including Iraq, the level of potable groundwater is constantly decreasing, and the rate of water flow in rivers is decreasing, which leads to a crisis in securing water, especially in the summer. The desalination process is the most important means for securing safe water for drinking and household uses from saline seawater or turbid groundwater. Consequently, it was necessary

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to find other sources of usable water. Now, two of the most available sources, namely the oceans, and seas, in addition to the large stock of groundwater deep in the earth [8]. It is evident that groundwater and seawater are not suitable for direct use because they contain high levels of salts and impurities that make their use difficult, if not impossible, in their normal condition [9]. Therefore, they must be rid of these impurities and salts to get fresh water [10].

There are currently many methods for desalinating salty water, but they consume a large amount of energy, so scientists and engineers have tried to use non-conventional energies as a source of energy in water desalination plants, particularly solar energy [11]. The distiller process using solar energy is one of the methods used from ancient times until now in the desalination of salty water, especially in isolated locations where it is challenging to find freshwater or the energy sources necessary to convert salty water into usable water [12]. The solar distiller system consists of a dye-coated horizontal basin or a substance that helps absorb heat energy from solar radiation. This basin has a transparent cover that tightly closes the air space formed above the distiller basin. This transparent cover, made of glass in most cases or of plastics at other times, is inclined towards a space where the resulting distilled water collects. The solar rays pass through the transparent cover, which absorbs part of these rays, and the other part is absorbed by the base of the solar distiller basin, which helps heat the water and evaporate it. The method of feeding water to the distiller can be done in two ways, one of which is feeding in the form of batches, and the other is continuous feeding. Many designs and ideas were presented to boost the amount of water that solar distillers produce [13]. One of these methods involves connecting the solar collector system to the solar distiller such that the water flowing into the solar distiller is heated by a solar collector [7]. Several articles used various solar collector types combined with solar distillers [14]. In a practical study on water desalination, a solar distiller with phase change material built within the solar collector was employed by Al-Harahsheh et al. [15] to enable continuous operation at night through the use of a heat exchanger positioned in the basin. About 40% of the water distilled by the solar distiller unit, which has a 4,300 mL/m^2·d capacity, comes after sunset. According to an economic study, these units are only practical in remote locations. Benhammou and Sahli [16] studied the performance of a solar distiller combined with a thermal storage system containing a phase change material to operate continuously throughout the day under Algerian environmental conditions. The outcomes confirmed that the storage system containing phase change material increased output by 63%. Abed et al. [17] studied how single-slope solar distiller performed using an ultrasonic evaporator, solar heater, and PCM capsules. As a result of using cylinder-shaped PCM capsules, water output was boosted by 30.6%. The findings also showed a 41.5% improvement in water output when the solar collector and high-frequency ultrasonic evaporator were used.

The analysis of a thermal system made up of a single-slope solar distiller coupled with an Evacuated cylindrical collector was researched by Kumar et al. [18]. The three depths (5, 10, and 15 cm) were examined. The annual water output was shown to increase with a decrease in the water depth, where a drop in water depth from 15 to 5 cm was found to result in a 22% gain in daily energy production. Amiri et al. [19] performed a thermal and economic evaluation for a novel solar distiller and concentrator solar collector design. According to the findings, the suggested solar system produces an average of 0.961 L of fresh water per day in the summer, 55% more than the yield of the other systems in the winter. Singh et al. [20] performed the energy analysis of a solar distiller combined with an evacuated cylindrical collector. The proposed system's daily energy and exergy efficiencies were 33.0% and 2.5%, respectively. Jaber et al. [21] used a PCM as wax to enhance the performance of a solar distiller integrated with an evacuated cylindrical collector. The findings indicate that the evacuated cylindrical collector-integrated solar distillers are more efficient than conventional solar distillers. Additionally, the trial findings showed that the PCM-equipped evacuated cylindrical collector increased production in the solar distillers by 40.7% and 38.93%, respectively. Alwan et al. [22] demonstrated a modified solar distiller design integrated with a flat solar collector. According to the findings, the proposed model was 292% more productive than the conventional designs. A performance evaluation of solar distillers integrated with evacuated tube solar collectors and utilizing perforated fins and pebbles was carried out by Panchal et al. [23]. According to the findings, the modified solar distiller's thermal efficiency outperformed the standard one by 2.32%. Dhivagar et al. [24] used a storage biomaterial to enhance the performance of the solar distiller. Results showed that compared to conventional distillers, solar distillers' overall productivity was 10.8% higher when using energy-storage biomaterials and porous media. Angappan et al. [25] accomplished an empirical and economic analysis of a solar distiller integrated with a solar cooker and studied the operational variables of the hybrid system's performance. The finding of the study confirmed an intensification in the production of freshwater by about 41% compared to the traditional distiller systems. Also, active solar distillers reduced CO_2 emissions by 41% compared to passive solar systems. The study also showed that the active and passive solar distillers produced 3.9 and 5.5 L/m^2 daily.

Essa et al. [26] enhanced the performance of the pyramid solar distiller utilizing a condenser, pyramidal absorber, mirrors, and thermal storage material. The outcomes demonstrated that mirrors and condenser provided the best performance, with productivity gains and distiller efficiencies of 142% and 52.5%, respectively. Abdullah et al. [27] used the various wick materials and electric heater to enhance the performance of the pyramid solar distiller. The major goal of this study was to determine how using different burlap wicks made of jute, cotton, plush, and silk fabrics affects the functionality of a modified solar distiller. the results confirmed that the highest values for the increase in productivity were for the distiller coupled with jute (125%), then cotton (115%), then plush (88%), then silk (60%), respectively. Abdullah et al. [27] enhanced the performance of the solar distiller utilizing a nano-PCM and wick finned absorber. Results showed that using heaters and phase change materials with nanoparticles increased modified distiller productivity by 166% and 136% as compared to that of the classical solar distiller, respectively. Omara et al. [28] achieved an experimental study to assess the performance of pyramid solar distiller using a dish absorbers and wick materials. Painting the absorber with black paint mixed with various nanocomposites of titanium oxide (TiO_2), copper oxide (CuO), and silver (Ag) allowed researchers to examine the effectiveness of the modified system. The results of the experiments showed that 15 cm was the ideal height for the modified dish absorber to achieve the highest performance. At this height, the productivity of the jute cloth-solar still system increased by 54%. Essa et al. [29] enhanced the performance of pyramid still using conical absorbing surface, thermal storing material, condenser, and reflectors. According to the findings, adding a modified conical absorber boosted the modified pyramid solar still's evaporative surface area by 14%. Additionally, it is advised to use jute cloth rather than cotton cloth as a wicking material for the modified solar still due to its improved performance, as the distillate of the modified system with cotton and jute wicks was raised by 66% and 69%, respectively, over that of the conventional distiller. Saeed et al. [30] used a nano-PCM and corrugated drum to enhance the performance of the drum solar distiller. The results confirmed that in comparison to an ordinary solar still, the experiment's results showed that a corrugated drum solar still using a corrugated drum, Ag-black paint, and PCM-Ag at 0.1 rpm produced a yield that was 318% larger. Saeed et al. [30] used a two types of fins to enhance the performance to the pyramidal solar distiller. The collected testing results showed that, under all test settings, the pyramidal solar stills with inclined perforated rectangular fins and hollow perforated cylindrical fins produced more distillate water than the classical solar distiller.

Parsa et al. [31] used nanoparticles coated at the interface of solar distiller absorbers to increase the solar energy absorber by the system. Findings showed that increasing the nanoparticle concentration to 5% was only sensible during the summer, from an economic standpoint, while the ideal concentration was 2.5% for autumn and spring. Also, several studies were conducted to integrate the PV/thermal solar panels with the solar distiller. Singh et al. [32] used two series-connected PV/thermal collectors to heat the water entering a solar collector. This system is suitable for homes in remote areas where it produces electricity and fresh water. Subramanian et al. [33] employed a flat plate collector to improve the solar distiller's efficiency. Regular solar distillers produced 1,610 mL/h. The proposed solar distiller system had an output of approximately 2,250 mL. However, it was more productive than the existing system by 50%. Gaur and Tiwari [34] carried out research to identify the ideal number of PV/thermal solar collectors suitable for the solar distiller. Based on exergy efficiency, it was discovered that water has a maximum output at $N = 4$ for 50 kg of water mass. Shoeibi et al. [35] used the PV/thermal collector integrated with heat pipes and thermoelectric generator to enhance the performance of the solar distiller. When these design improvements were used, the results specified an enhancement in the amount of water produced and the electrical power generated in the voltaic panels.

The most important characteristic of solar distillers is their low efficiency. Increasing the production of solar distillers is the main concern of researchers and scientists, and there are many designs to achieve this goal, such as connecting solar distillers to solar collectors or using porous media or nanomaterials, and others. It has been noted through reviewing previously published papers that there is a lack of studies or articles about how to make solar distillers function better by using two kinds of solar collectors [36]. Two kinds of solar collectors have been utilized: evacuated cylindrical collectors and parabolic solar collectors. The effect of the two types of solar water heaters on the performance of the simple solar distiller will be compared. The novelty in the current article is the study of the performance of the solar distiller system integrated with two different types of solar collectors with a study of the effect of changing the flow rate under hot weather suffering from a shortage in water. The research was carried out at Kirkuk, northern Iraq, at (35°28′°N 44°24′°E), where Iraq suffers in general from a scarcity of rain as a result of climate change and the presence of groundwater with a salty percentage that needs treatment for suitability for human use [37].

2. Methodology

The use of solar energy to provide basic human needs such as water and electricity has become one of the most significant goals of countries to reduce economic costs, especially in remote areas. To easily understand whether these systems might be utilized for residential purposes, this article will evaluate the influence of utilizing two different types of solar collectors on solar distiller performance. Two models of traditional solar distillers were built, and one was connected to two dissimilar forms of solar collectors for each case to obtain the highest productivity of the system. Two types of solar collectors were chosen: An evacuated cylindrical collector and a Parabolic concentrator collector. The article has been arranged as follows: section 3 will thoroughly explain the experimental design and briefly explain the measurement tools employed. Calculating the performance equations and system efficiencies for the entire system will be covered in section 4. Section 5 will discuss the findings related to the scientific explanation, and section 6 will brief the conclusions and suggestions for further future research. Fig. 1 represents the flow chart of the current study. The experiments were carried out under the climatic conditions of the Iraqi city of Kirkuk (35.46°N, 44.39°E)

3. Experimental work

From August to October 2021, there have been experiments at the technical college in Kirkuk, northern Iraq. The experimental system consists of three main parts (Fig. 2a–d).

3.1. Solar evacuated cylindrical collector

The solar heater comprises 36 evacuated tubes, each measuring 180 cm in length, 58 mm in outer diameter, and 47 mm in inner diameter. Each tube holds 1.5 L of water. The solar heater system includes a main tank containing 36 holes to insert evacuated tubes and a hole containing rubber to prevent water leakage. The tank length was (245 cm), and its outer diameter was (40 cm). The tank has two points for entering and leaving the water from it. A second, smaller upper tank is connected to the two entry locations to maintain the hot water.

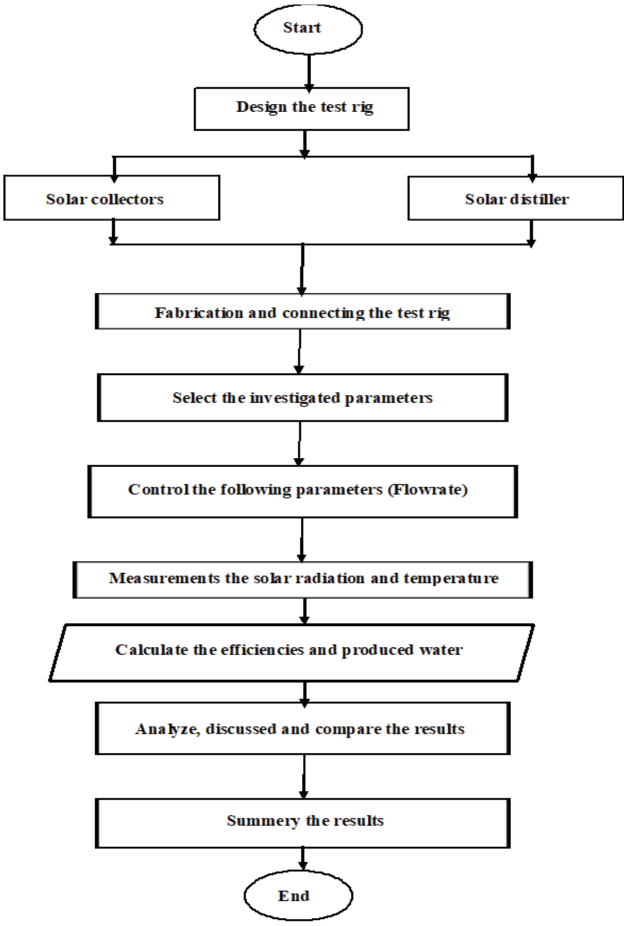

Fig. 1. Flow chart of the study.

3.2. Parabolic concentrator collector

The technical parameters were used to build and manufacture a model of a cylindrical parabolic solar collector locally: its length is (190 cm), its width is (100 cm), and the centre depth is (25 cm). The focal length (*f*) of the copper tube with glass is 25 cm, while the copper tube's overall length is 176 cm. The tracking system was hand-operated, the collector was directed towards the south, and the solar concentrator was above the ground at (110 cm).

3.3. Solar distiller

Two identical solar double-slope distillers were manufactured, one connected to the parabolic concentrator collector system through a heat exchanger inside the distiller. An evacuated cylindrical collector was attached to the second solar distiller. The performance of these distillers was compared with the performance of another solar distiller without any connection with the solar collector to demonstrate the actual effect of the external solar collectors. The basin was made from sheets of sturdy galvanized steel that had a thickness of 3 mm. The glass was inclined at 35° from the horizon, and the base area measured (100 cm × 90 cm × 20 cm). The glass cover has been fixed with a sealant to prevent moist hot air from escaping the solar distiller. The solar distiller's basins were also isolated using a thermal insulator to reduce heat loss to the outside environment. A heat exchanger was installed at the base of the solar distiller basin to disperse the heat from the solar collectors to the water in the distiller basin, as shown in Fig. 2b. Black paint has been applied to the bottom of the distiller basins to maximize the thermal absorption of solar radiation. 10 thermocouples were employed to gauge the temperature in various system components, as shown in Fig. 2c and d. A special pump was utilized to circulate the water inside the system, and a flowmeter measured the water flow. The velocity of the water inside the system was controlled by a selective switch that set three different speeds.

3.4. Procedure method of the experiments

Several practical tests were conducted on the proposed solar distillers, where the following were measured:

- Measuring temperatures at different points of the solar distillers and the entry and exit points of each type of solar collector and the heat exchanger.
- Measuring the intensity of solar radiation.
- Measuring the ambient air temperature.
- Measure the amount of distilled water.
- Measuring the water level inside the solar distillers.

4. Performance calculations

A performance formulation for the system's three main components has been developed to test its performance under various working situations:

4.1. Thermal efficiency of evacuated cylindrical collector

The useful heat collected by the evacuated cylindrical collector was obtained as follows [38]:

$$Q_{\text{evacuated}} = \dot{m}C_p\left(T_{\text{evacuated},O} - T_{\text{evacuated},i}\right) \tag{1}$$

where $\dot{m}$, the mass flow rate of flowing water inside the solar collector and measured using a rotameter. C_p, the specific heat of the water, and calculate from Eq. (2) [39]:

$$C_p = 4.1855\times10^3\left[0.966185 + 0.0002874\left(\frac{(T-173)}{100}\right)^{5.26}\right] \tag{2}$$

$T_{\text{evacuated},o}$, $T_{\text{evacuated},i}$ the outlet and inlet water temperature of the solar collector, respectively.

The thermal efficiency of the solar evacuated cylindrical collector is evaluated from the equation [40]:

$$\eta_{\text{evacuated}} = \frac{\dot{m}C_p\left(T_{f,O} - T_{f,i}\right)}{A_{\text{evacuated}} \cdot I_b} \tag{3}$$

where $A_{\text{evacuated}}$, the surface area of the evacuated cylindrical collector facing the sun. I_b, the value of the incident solar radiation.

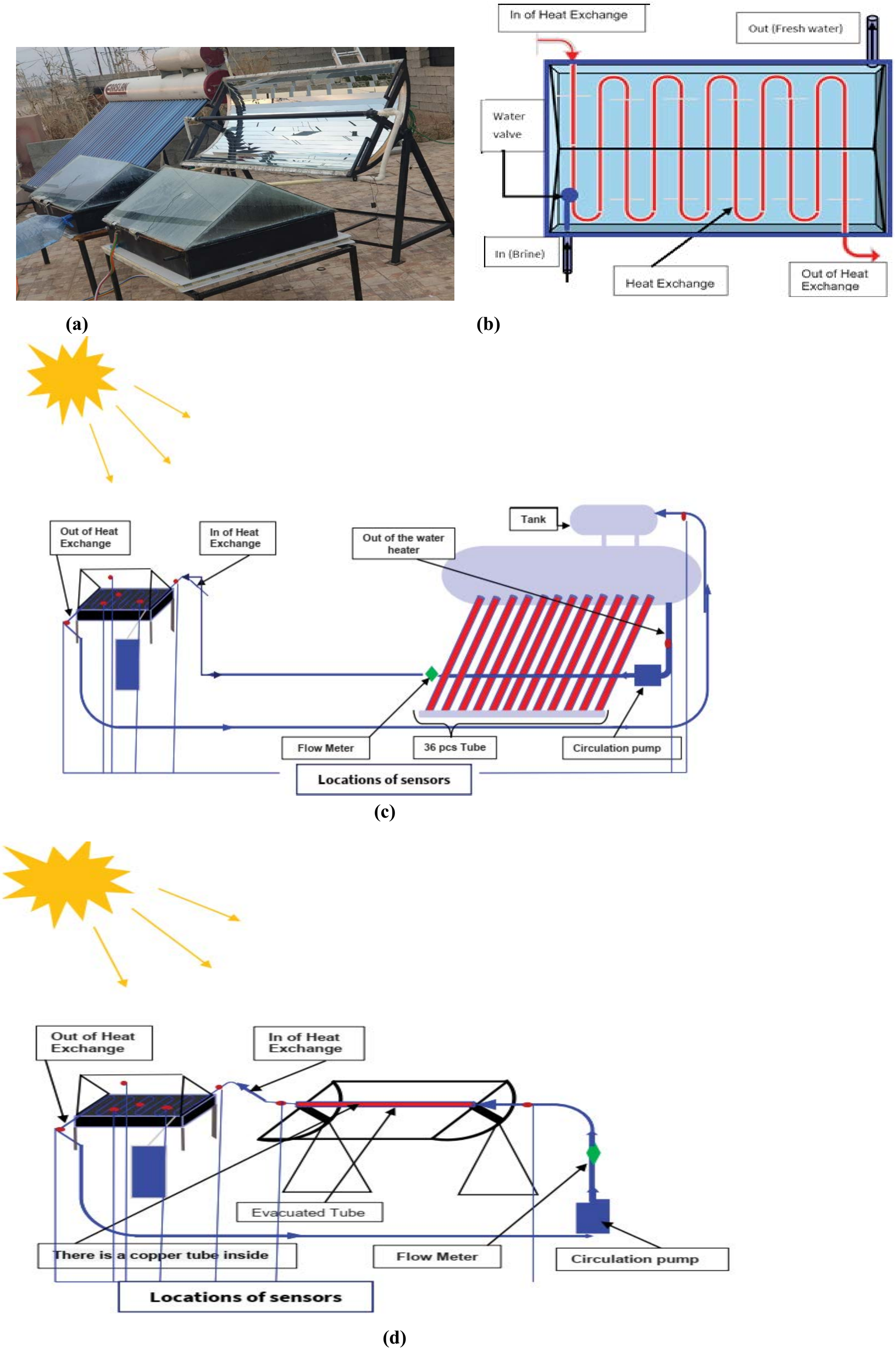

Fig. 2. Detail of the experimental work. (a) A photograph of the proposed system, (b) top view of the heat exchanger for the distiller basin, (c) the solar still connected to the evacuated cylindrical collector, and (d) the solar still connected to the parabolic concentrator collector.

4.2. Thermal efficiency of parabolic concentrator collector

The following equation has been used to determine the evacuated cylindrical collector's thermal efficiency [41]:

$$\eta_{\text{parabolic}} = \frac{\dot{m}C_p\left(T_{\text{parabolic},O} - T_{\text{parabolic},i}\right)}{A_{\text{parabolic}} \cdot I_b} \tag{4}$$

where $T_{\text{parabolic},i}$, $T_{\text{parabolic},o}$, the temperatures of the inlet and outlet water of the evacuated cylindrical collector, respectively.

4.2. Thermal efficiency of solar distiller

The efficiency of a simple solar distiller can be written from the Eq. (5) [42]:

$$\eta_{\text{still}} = \frac{m_{\text{ew}} \times h_{\text{fg}}}{I_b A_{\text{still}}} \tag{5}$$

A_{still}, the horizontal projection area of the solar distiller; h_{fg}, latent heat of vaporization at the brine water temperature for the basin; m_{ew}, The hourly average of distilled water.

The pure water produced in the solar distillers during the day can be calculated from the following relationship [43]:

$$M_{\text{ew}} = \sum_{t=1}^{24} m_{\text{ew}} \tag{6}$$

The overall efficiency has been calculated as follows [43]:

$$\eta_{\text{overall}} = \eta_{\text{still}} + \eta_{\text{parabolic}} + \eta_{\text{evacuated}} \tag{7}$$

The error percentage for each measuring equipment stated in Table 1 must be ascertained to guarantee the validity and accuracy of the measurements taken using the existing system. The unreliability of the test findings is calculated using the relation [44]:

$$U_R = \sqrt{\left(\frac{\partial w}{\partial x_1} \times \varphi_1\right)^2 + \left(\frac{\partial w}{\partial x_2} \times \varphi_2\right)^2 + \cdots + \left(\frac{\partial w}{\partial x_n} \times \varphi_n\right)^2} \tag{8}$$

The uncertainties of the major parameters of the experimental measurement and results were confirmed, as shown in Table 2.

5. Results and discussions

Two identical solar distiller models, one integrated with two different types of solar collectors and the other single with no connection, were made to show the solar collector's true influence on the solar distillers' efficacy. A set of practical tests were conducted on the solar distillers used in the article:

- The first case: Solar distiller connected with the parabolic concentrator collector and its comparison with the performance of traditional solar distiller.
- The second case: Solar distiller connected with the evacuated cylindrical collector and its comparison with the performance of traditional solar distiller.

5.1. Solar distiller integrated with the parabolic concentrator collector (first case)

5.1.1. Temperatures of the system

Fig. 3 clarifies the change in the basin water temperature of the distiller connected to the parabolic concentrator collector (m_1) and the temperature of the basin water of the traditional distiller (m_2). It has been noted that the rise in solar radiation values caused the basin water temperature to rise in both kinds of solar distillers, reaching its peak value at 2 p.m. (Fig. 3a). When connected to a parabolic concentrator collector, the solar distiller's basin water was of a slightly higher temperature than the conventional solar distiller. The rise in water temperature in the basin is a reliable sign that the solar distiller's efficiency has improved. It should be mentioned that the temperature of the basin water increased during the morning and peaked at 2 p.m. as a result of an increase in solar radiation. The water basin's temperature drops after 2 p.m. as a result of less sun radiation and higher heat losses. The water in the solar distiller basin connected to the parabolic concentrator collector reached a maximum temperature of about 71°C. The temperature of the water basin drops as the mass flow of water in the heat exchanger increases, as shown in Fig. 3b.

Additionally, the water in the basin reaches its greatest temperature at 1 p.m. rather than 2 p.m., as was the case in the prior instance due to an increase in the water's flow rate feeding the distiller. Increasing the temperature of the basin water is useless unless the glass cover is cooled to obtain a thermal difference to produce the largest amount of distilled water. In certain experiments, the thermal insulator attached to the distiller basin's exterior surface to act as thermal insulation was removed to show how thermal insulation affects the temperature change inside the distiller. Fig. 4 represents the temperature change inside the basin of the solar distiller. The similarity of the temperature change behavior of the basin water is noted for the comparison

Table 1
Instrument specifications

Equipment	Measurement	Error
Solar radiation	Solar radiation	±9 W/m^2
Rotameter	Mass flow rate of water	±3.5%
Digital thermometer	Temperature	±0.6°C

Table 2
Experimental parameters' unpredictability

Measured variable	Relative uncertainty %
Temperature	±2.5
Solar radiation intensity	±4
Total efficiency	±5
Thermal efficiency	±4
Mass flow rate	4%

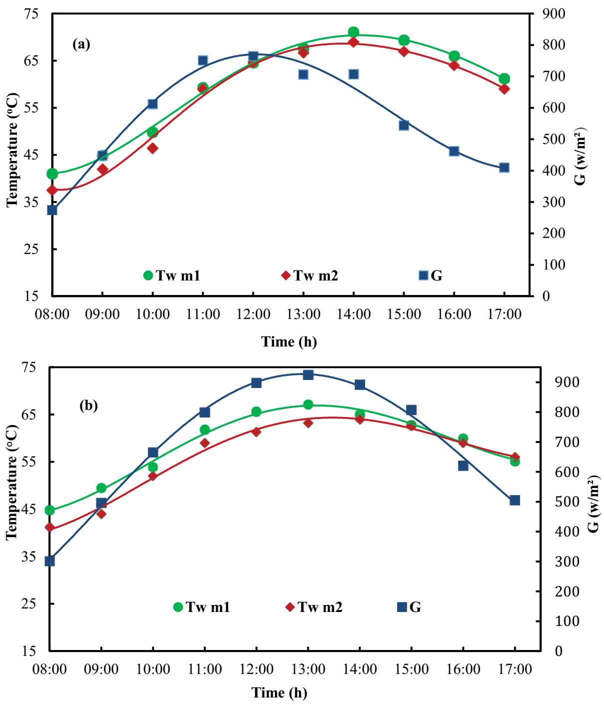

Fig. 3. Water temperature and solar radiation with time for the two insulated distillers. (a) $\dot{V}$ = 1.4 L/min, water basin height is 5 cm and (b) $\dot{V}$ = 2 L/min, water basin height is 5 cm.

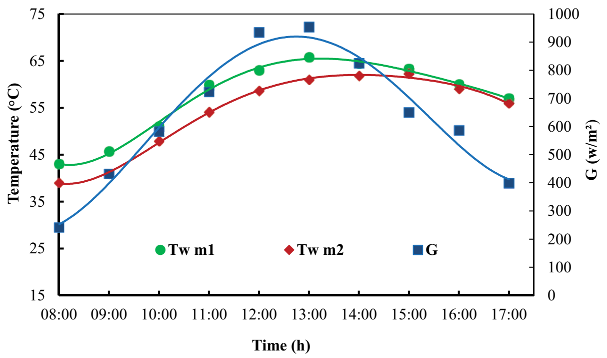

Fig. 4. Distribution of temperature and solar radiation for non-isolated distillers ($\dot{V}$ at a flow of 2 L/min, water basin height is 5 cm).

between Figs. 3b and 4, as the productivity of solar distillers depends largely on the quality of thermal insulation. The values of the basin water temperatures in the isolated solar distillers were higher than the non-isolated solar distiller in general, and these behaviors are consistent with previously published results such as [45].

5.2. Water production of solar distiller connected with parabolic concentrator collector

Fig. 5 represents the water production of solar distillers. The solar distiller connected to a parabolic concentrator collector is the first and notated as (m_1); the conventional solar is the second and notated as (m_2). The ultimate water production of the conventional solar distiller was 1.26 E-04 L/s at

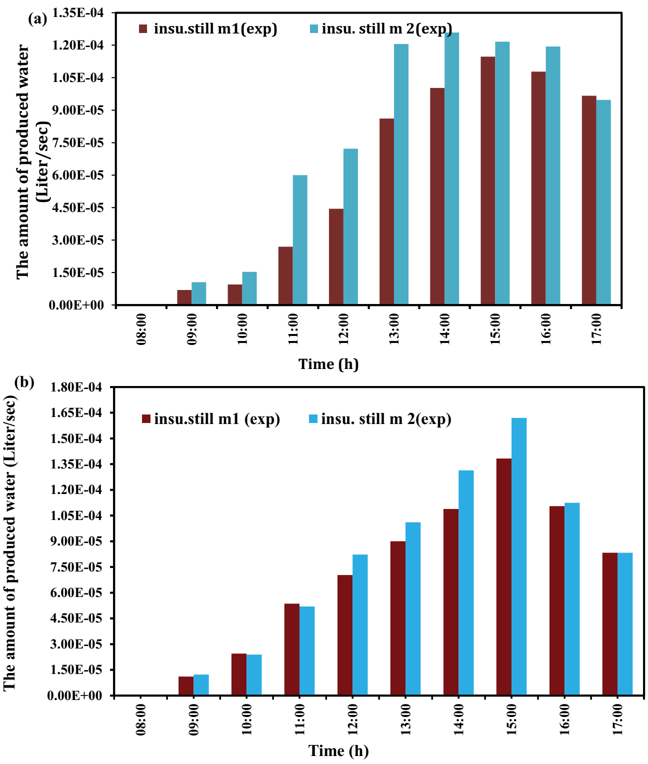

Fig. 5. Water production of solar distillers with time (case 1). (a) Flow of 1.4 L/min, water height in the basin 5 cm and (b) a flow of 2 L/min, water height in the basin 5 cm.

2 p.m., whereas the maximum water production of the conventional solar distiller was 1.15 E-04 L/s at 3 p.m. (Fig. 5a). It has been observed that the conventional solar distiller produced more water than the solar distiller connected to a parabolic concentrator collector. The water temperature of the distiller connected to the evacuated cylindrical collector is greater than the water temperature of the traditional distiller basin, which is the reason for this behavior.

According to Muftah et al. [46], A solar production distiller is improved by increasing the temperature difference between the water in the basin and the glass cover. Fig. 5b illustrates how raising the heat exchanger's cooling water flow also improves the performance of the solar distiller, which is attached to the parabolic concentrator collector. The ultimate water production of the conventional solar distiller was 1.62 E-04 L/s at 3 p.m., whereas the maximum water production of the solar distiller connected with a parabolic concentrator collector was 1.38 E-04 L/s at 3 p.m. This increase in water production is because the increase in the cooling water flow rate in the heat exchanger causes an increase in the difference between the temperature of the basin water and the glass cover [47].

5.3. Solar distiller integrated with the Evacuated cylindrical collector (second case)

5.2.1. Temperatures of the system

Fig. 6a shows the differences in water temperature between the distillers attached to the evacuated cylindrical collector and the conventional solar distillers. The water basin of the solar distiller gets hotter when it is connected to an evacuated cylindrical collector. The highest temperature of the water in the distiller basin was 71°C at 3 p.m. compared to the highest temperature in the traditional solar distiller basin, which was 66°C. The same behavior continued when the flow rate of moving water inside the closed system was increased from 1.4 to 2 L/min, as in Fig. 6b. When comparing the solar distiller connected to the evacuated cylindrical collector and the distiller connected to the evacuated solar collector, it has been noted that the water temperature of the two basins was similar, and therefore the use of either type gives the same basin temperatures. The water in the basin is heated as a result of the sun's rays falling. Its temperature rises to a level higher than the temperature of the glass cover and higher than the temperature of the air inside the basin between the surface of the water and the glass cover. As the water vapor pressure rises with the temperature rise, the water vapor pressure in the water is higher than the temperature of the water inside the basin. As a result of this difference in pressure between the layer of steam in contact with the surface of the water in the basin and the steam in the air, the water in the basin begins to evaporate to equalize the steam pressure inside the basin.

5.2.2. Water production of solar distiller connected with the evacuated cylindrical collector

Fig. 7a clarifies the water production of solar distillers. The first is the solar distiller connected to an evacuated cylindrical collector (m_1), and the second is the classical solar distiller (m_2). The ultimate water production of the classical solar distiller was 1.29 E-04 L/s at 2 p.m., whereas the ultimate water production of the hybrid solar distiller was 1.21 E-04 L/s at 4 p.m. It has been noted that the water production of the conventional solar distiller was higher than the solar distiller connected to the evacuated solar collector. This behaviour is because the water temperature of the distiller basin connected to the evacuated cylindrical collector is higher than that of the classical distiller basin. Increasing the difference in temperature between the temperature of the basin water and the glass cover leads to an increase in the output of the solar distiller [24]. As illustrated in Fig. 7b, increasing the cooling water flow in the heat exchanger also enhances the solar water production distiller attached to the evacuated cylindrical collector. The ultimate water production of the classical solar distiller was 1.29 E-04 L/s at 2 p.m., whereas the ultimate water production of the hybrid solar distiller was 1.48 E-04 L/s at 5 p.m. It was also noted that the hybrid solar distillers have higher productivity than the traditional distillers after 3:00 p.m. in the afternoon due to the low temperature of the glass cover and the high temperature of a water basin.

5.4. Efficiency of the model

Thermal efficiency is the most substantial variable by which the dissimilar designs of solar thermal systems can be compared. The thermal efficiency of the designs proposed in the present article has been calculated by Eq. (5). Table 3 represents the thermal efficiency of the solar distiller (when the flow rate was 1.4 L/min), while Table 4 represents the

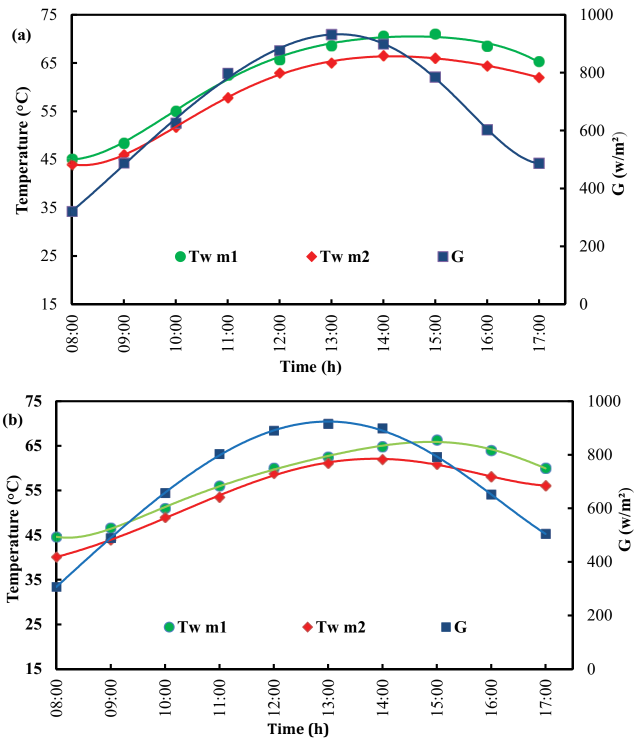

Fig. 6. Change of water temperature of the basin and solar radiation for the two insulated distillers. (a) $\dot{V}$ = 1.4 L/min, water basin height is 5 cm and $\dot{V}$ = 2 L/min, water basin height is 5 cm.

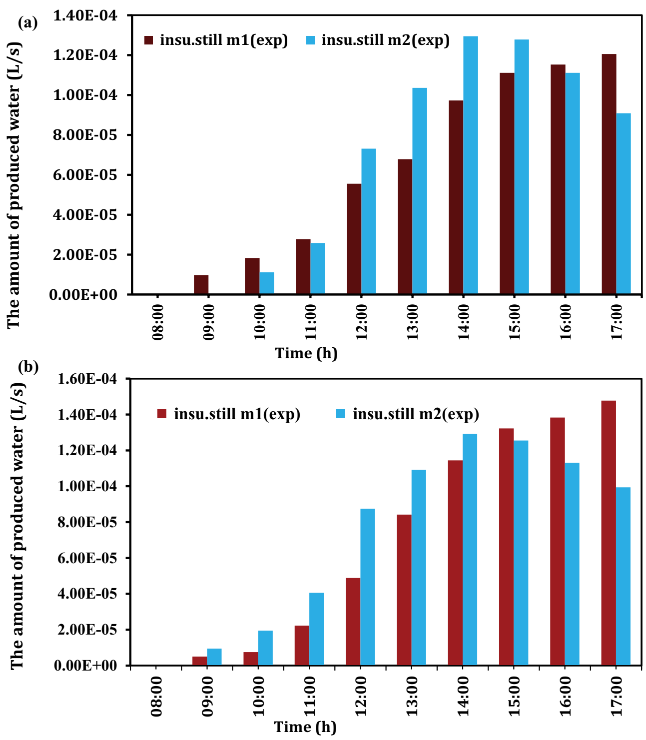

Fig. 7. Output of solar distillers with time (case 2). (a) Flow of 1.4 L/min, water height in the basin 5 cm and (b) a flow of 2 L/min, water height in the basin 5 cm.

thermal efficiency of the solar distiller (when the flow rate was 2 L/min). It has been noted from the two tables that thermal efficiency was at its highest value in the late hours of the day in all the designs presented in the current article. It has also been noted that the addition of solar collectors (parabolic concentrator collector and evacuated cylindrical collector) does not affect the efficiency of the solar distiller. The results showed that connecting the conventional solar

Table 3
Solar distiller efficiency (%) (flow of 1.4 L/min)

Time	Solar distiller + parabolic concentrator collector	Conventional solar distiller	Solar distiller + evacuated cylindrical collector	Conventional solar distiller
8:00	0.0	0.0	0.0	0.0
9:00	4.1	6.3	5.3	1.9
10:00	4.1	6.6	7.7	4.7
11:00	9.4	21.0	9.1	8.5
12:00	15.2	24.6	16.5	21.8
13:00	28.9	44.4	18.9	29.0
14:00	36.7	46.2	28.0	37.5
15:00	51.5	58.2	36.7	42.4
16:00	60.8	67.5	49.7	48.1
17:00	61.7	69.6	64.5	48.8
Average	27.24	34.44	23.64	24.27

Table 4
Solar distiller efficiency for (%) (flow of 2 L/min)

Time	Solar distiller + parabolic concentrator collector	Conventional solar distiller	Solar distiller + evacuated cylindrical collector	Conventional solar distiller
8:00	0.0	0.0	0.0	0.0
9:00	5.9	6.6	2.7	5.1
10:00	9.7	9.5	3.0	7.8
11:00	17.6	17.1	7.3	13.3
12:00	20.4	24.0	14.4	25.8
13:00	25.3	28.6	24.0	31.2
14:00	31.8	38.4	33.2	37.6
15:00	44.8	52.4	43.5	41.6
16:00	46.6	47.5	55.5	45.6
17:00	43.4	43.3	76.7	51.8
Average	24.55	26.74	26.03	25.98

Table 5
Comparing the efficiency of the current arrangement with the efficiency of systems in available studies

	Study type	Solar distiller + parabolic concentrator collector	Solar distiller + evacuated cylindrical collector	Solar distiller + PV/T collector
Current study (1.4 L/min)	Experimental	27.24%	23.64%	–
The current study (2 L/min)	Experimental	24.55%	26.03%	–
Singh et al. [20]	Theoretical	–	33.0%	–
Hassan et al. [48]	Experimental	20.03%	–	–
Gaur and Tiwari [34]	Theoretical	–	–	26%
Mazraeh et al. [49]	Theoretical	–	–	17%
Singh et al. [32]	Experimental	–	–	25%
Kumar et al. [18]	Experimental	16.6%	–	–
Fallahzadeh et al. [1]	Experimental		14%	

distiller with different solar collectors has no significant benefit. A method of cooling the glass cover must be added to the solar distillers integrated with the solar collectors to improve their performance and get the intended benefits from these integrated systems. The results also show that the efficiency of the solar distiller attached to an evacuated solar collector grows with an increase in cooling water flow rate, while the efficiency of the solar distiller connected to a parabolic concentrator collector drops. The maximum daily efficiency of the solar distiller was for the conventional design, which was 34.44%. The current system has higher thermal efficiency than previous studies, as shown in Table 5.

6. Conclusions and upcoming projects

Enhancing the productivity of the solar distiller by introducing new system designs is very important due to the continuous need to increase the production of fresh water. Therefore, one of the essential directions of the present article is to study the performance of the solar distiller, which is linked to two different types of solar distiller, and to study some of the operational variables and to indicate the desired benefit from them. The following findings can be drawn from the experiments carried out for this study.

- The temperature of the basin water of the solar distiller, which is connected to the two types of solar collectors, was barely higher than the ordinary solar distiller.
- The increase in the basin water temperature is a good indicator of the improvement in the effectiveness of the solar distiller.
- It has been noted that thermal efficiency was at its highest value in the late hours of the day in all the designs presented in the current article.
- It has also been noted that the integration of solar collectors (parabolic concentrator collector and Evacuated cylindrical collector) does not affect the productivity of the solar distiller.
- To enhance the performance of the solar distillers integrated with the solar collectors, a means must be further to cool the glass cover to obtain the desired benefit from these integrated systems.
- For upcoming studies, it is recommended to study a new method for reducing the glass cover temperature to obtain the desired benefit from these integrated systems and increase the system's effectiveness.
- Study the economic possibility of the proposed system in the current article and compare the cost of the current system with the economic cost of other solar distiller systems.

Symbols

$A_{\text{evacuated}}$	—	Evacuated cylindrical collector's surface area, m^2
$A_{\text{parabolic}}$	—	Parabolic concentrator collector's surface area, m^2
A_{still}	—	Denotes the horizontal projection area of the distiller, m^2
C_p	—	Specific thermal heat of the water, J/kg·s
h_{fg}	—	Latent heat of vaporization at the brine water temperature for the basin, J
m_{ew}	—	Hourly average of distilled water, kg
$\dot{m}$	—	Mass flow rate of flowing water inside the system, kg/s
M_{ew}	—	Quantity of distilled water collected during the day, kg/d
$T_{\text{evacuated}}$	—	Evacuated cylindrical collector's useful heat, W
$T_{\text{evacuated},o}$	—	Temperature of the outlet water of the evacuated cylindrical collector, °C
$T_{\text{evacuated},i}$	—	Temperature of the evacuated cylindrical collector's intake water, °C
$T_{\text{parabolic},i}$	—	Temperature of the inlet water of the parabolic concentrator collector, °C
$T_{\text{parabolic},o}$	—	Temperature of the outlet water of the parabolic concentrator collector, °C
I_b	—	Incident solar radiation, W/m^2
$\eta_{\text{evacuated}}$	—	Solar evacuated cylindrical collector's thermal efficiency, %
$\eta_{\text{parabolic}}$	—	Evacuated cylindrical collector's thermal efficiency, %
η_{still}	—	Simple solar distiller's efficiency, %
η_{overall}	—	System's overall efficiency, %

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