

Experimental investigation of simultaneous effect of parabolic trough collector and flat external reflectors on performance of stepped solar still

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ABSTRACT

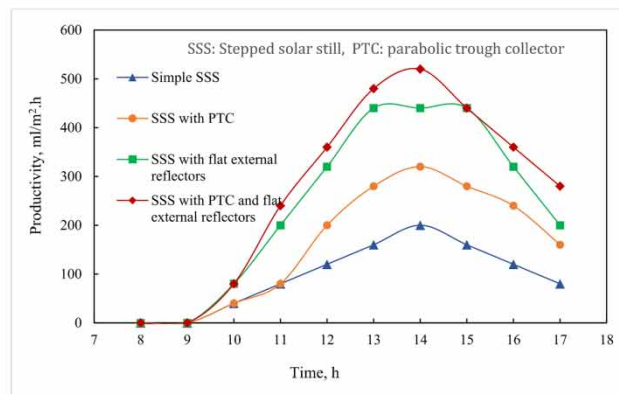
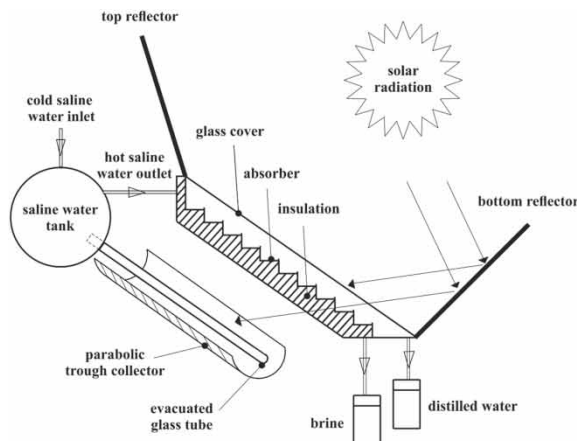
In this research, the performance of a stepped solar still has been experimentally evaluated. For this purpose, a parabolic trough collector has been used to preheat the saline water entering the solar still. Also, two flat external reflectors have been employed to increase the amount of solar energy received by the steps and the collector of the system. The findings of this research indicate that the use of two flat external reflectors is more effective than using the trough collector. Also, it is more efficient to apply both mechanisms simultaneously than to use them separately. According to the obtained results, the distilled water output of the solar still is 760, 1,560, 2,440 and 2,760 ml/m², respectively, for operating the conventional solar still, using the trough collector, using the two flat external reflectors, and using the collector and reflectors simultaneously. The electrical conductivity due to the presence of salt and chemical substances dissolved in the distilled water discharged from the still is 255, 215, 62 and 38 micro Siemens per centimetre, respectively, for each of the four mentioned cases. These experiments show that by applying the proposed mechanisms, the amount of distilled water can be increased, and its purity can be enhanced.

Key words: desalination, efficiency enhancement, flat external reflector, parabolic trough collector, stepped solar still

HIGHLIGHTS

- Performance of a stepped solar still (SSS) has been experimentally evaluated.
- Simultaneous effects of flat reflectors and PTC on the efficiency of the SSS have been studied.
- By combining the PTC with the flat reflectors, the distilled water output of the examined SSS is enhanced.
- Increasing the received solar radiation by the SSS and raising its working temperature seem to better purify the distilled water.

GRAPHICAL ABSTRACT



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NOMENCLATURE

A	area, m ²
C	specific heat, J/kg K
h	heat transfer coefficient, W/m ² K
h_{fg}	enthalpy of evaporation at T_w , J/kg
I_b	beam solar radiation (W/m ²)
I_d	diffuse solar radiation (W/m ²)
$I(t)$	total solar radiation on inclined surface, W/m ²
K	thermal conductivity (W/m°C)
L	thickness of insulation, m
m	mass, kg
\dot{m}_{ew}	hourly productivity, kg/h
n_d	number of day
P	partial pressure, N/m ²
Q	heat transfer, W
S_c	solar constant
T	temperature, °C
T	time, h
U	heat loss coefficient from basin and sides to ambient, W/m ² K
V	wind velocity, m/s
W	the tray width, mm

GREEK

α	absorptivity, dimensionless
β	glass cover inclination, degree
δ	declination, degree
φ	latitude, degree
ω	hour angle, degree
θ	incident angle, degree
τ	coefficient
ρ	density, kg/m ³
ϵ	emissivity, dimensionless
σ	Stefan-Boltzmann constant, (5.6697×10^{-8} W/m ² k ⁴)
η_d	daily efficiency of the still, %

SUBSCRIPTS

a	ambient
b	basin
c	convective
e	evaporative
fw	feed water
g	glass
r	radiative
w	water

1. INTRODUCTION

Today, the crisis of potable water shortage seriously threatens the lives of millions of people and wildlife throughout the planet. Numerous solutions have already been suggested and applied to deal with this crisis. One solution is the use of active and passive solar stills and desalination units to provide distilled potable water in remote and deprived areas. However, due to the low efficiency of these devices, they have been subjected to various tests and optimization procedures in recent years. The goal of such optimizations is to increase the amount of distilled water produced by these solar stills and to enhance their efficiency. Many parameters are involved in improving the efficiency of these systems, and different approaches have been proposed for optimizing such parameters.

One way of enhancing the productivity of solar stills is to preheat the inlet water that enters the steps of a solar still. Trough type solar collectors can be used for this purpose. In research work, [Abdel-Rehim & Lasheen \(2007\)](#) used a parabolic collector with focal pipe in a pool-type solar still to heat the floor of the device and achieved an 18% increase in the amount of distilled water produced by the still. They selected oil as the working fluid that flowed as a cycle through the focal pipe and serpentine. [Xiong *et al.* \(2013\)](#) used 14 evacuated glass tubes in the lower level of their 2-level solar still. In this system, by receiving heat energy through the glass cover in the upper level and from the vacuum tubes in the lower level, they were able to increase the still's efficiency and to produce distilled water during night time. [Kumar *et al.* \(2014\)](#) used a number of evacuated glass tubes in their pool-type solar still. In this experiment, they produced 3.47 kg of distilled water per day. [Panchal \(2015\)](#) employed 14 evacuated glass tubes in their pool-type solar still and boosted the efficiency of the system by 56% relative to the passive mode. [Yari *et al.* \(2016\)](#) analyzed a solar still equipped with evacuated glass tubes and transparent solar panels. According to their findings, transparent solar panels did not have a significant effect on distilled water and the maximum amount of distilled water produced daily by this system was 4.77 kg/m² for 30 numbers of tubes. [Saettone *et al.* \(2017\)](#) used 5 horizontal evacuated glass tubes to heat the saline water entering the steps of their designed solar still. Their experiment led to a 31.8% increase in the system's distilled water production. [Fathy *et al.* \(2018\)](#) employed a rotating parabolic collector with oil as a working fluid to heat the steps of a two-way pool-type solar still. By applying this technique, the distilled water output was increased by 142.3% relative to the passive mode. They demonstrated that the still efficiency in a hot climate is higher than in a cold climate. [Feilizadeh *et al.* \(2019\)](#) used 24 large-size evacuated glass tubes along with a reinforced condenser above their active thermo-syphoned solar still and produced 16.98 kg/m² of distilled water per day (an increase of 66% in water productivity).

[Madiouli *et al.* \(2020\)](#) examined the performance of a conventional single slope solar still and the impact of integrating a flat plate collector as well as a parabolic trough collector supported with a packaged glass ball layer. The modified solar still found to have increased productivity by 172% in winter and 203% in summer. [Hassan *et al.* \(2020\)](#) performed experimental work on a solar still incorporated with parabolic trough collector where it raised the daily productivity by about 12.1% and 5.9%, respectively in summer and winter. [Amiri *et al.* \(2021\)](#) developed an unsteady thermal model to theoretically study standalone desalination which was composed of a parabolic trough collector. [El Mahallawy *et al.* \(2020\)](#) examined a group of materials to determine the best metallic reflector for parabolic trough solar collectors of water desalination units. It was shown that the highest desalination rate is obtained by aluminium foil of thickness 6 µm. [Kumar *et al.* \(2020\)](#) have investigated an experimental study of a single slope solar still coupled with a parabolic trough collector for different brine depths. They declared that reduction in water level from 15 to 5 cm leads to increase in daily energy yield of 22%.

Another effective technique for enhancing the efficiency of solar stills is to increase the amount of solar energy received by using flat external reflectors. Numerous research works have been conducted in this regard, including numerical modeling and experimental tests. [Khalifa & Ibrahim \(2009\)](#) used internal and external reflectors in their pool-type solar still and respectively produced up to 19.9 and 34.8% more distilled water by the still equipped with internal reflector and the one using both the internal and external reflectors. By employing external and internal reflectors in a pool-type solar still, [Tanaka \(2009\)](#) boosted the production of distilled water by 70–100% during the winter season. In an experiment, [Omara *et al.* \(2014\)](#) simultaneously used internal and external reflectors in a stepped solar still and increased the system's distilled water output by 125% relative to a conventional pool-type still. [El-Samadony *et al.* \(2015\)](#) employed a condenser along with internal and external reflectors in the structure of their still system. Relative to a passive pool-type solar still, they achieved 66, 108 and 165% more distilled water, respectively, by using just the condenser outside the still unit, using both the external and internal reflectors, and simultaneously using the condenser and the reflectors. [Maiti *et al.* \(2016\)](#) used two flat external reflectors in stepped solar still and increased the distilled water output from 2.95 to 5.95 litre/day. [Gnanaraj *et al.* \(2017\)](#) employed two external reflectors in their stepped solar still and reported distilled water production of 4,333 and 5,650 ml/day for the conventional still (without reflectors) and the still system with reflectors, respectively. [Katabchi *et al.* \(2019\)](#) used two flat external reflectors along with a tubular condenser on the glass of stepped solar still. Their goal was to reduce the temperature of the glass and boost the condensation rate. They discovered that the external reflectors have their greatest influence during the winter, while the condenser on the glass is more effective in the spring season. The maximum distilled water output of this system (4.2 kg/m²) was achieved in the spring season, when the top and the bottom reflectors were tilted 10° and 45° relative to vertical and horizontal axes, respectively. [Patel *et al.* \(2020\)](#) investigated solar thermal effect of double slope solar still integrated with external reflectors. The thermal efficiency of a modified solar still was increased about 10.4% in summer and 10.0% in winter. [Shmroukh & Ookawara \(2020\)](#) evaluated the effect of combining stepped solar still with internal and

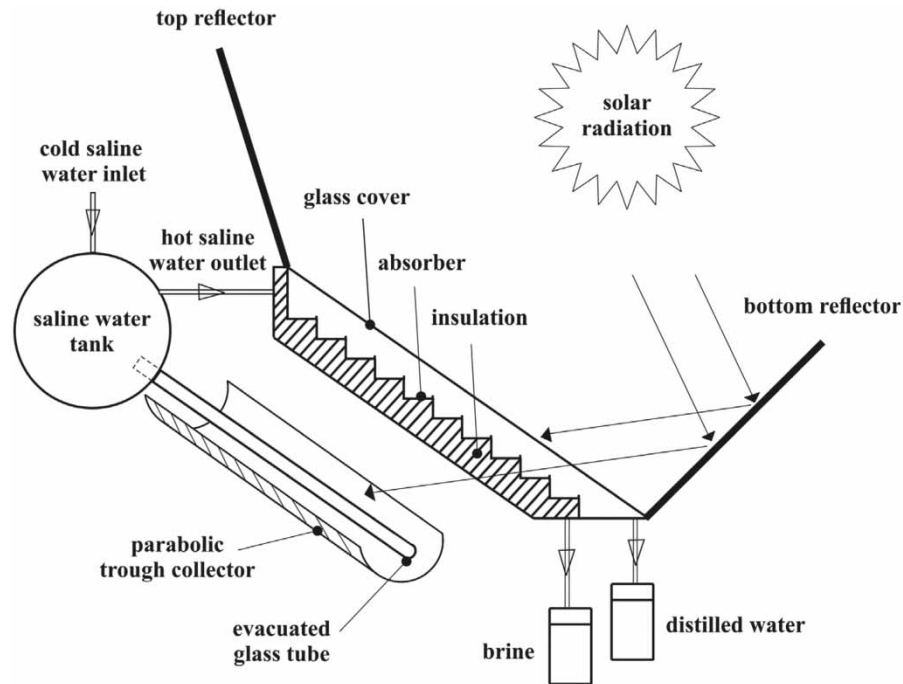


Figure 1 | Schematic of the solar still unit designed and built in this research.

external reflectors, copper fins, and transparent step walls on water productivity and daily efficiency. The experimental results revealed that the new stepped solar still attained 129% increase in fresh water production compared with the conventional still. Elashmawy (2020) studied tabular solar still equipped with tracking parabolic collector. The solar still had gravel as storage material. The results showed that utilizing tracking parabolic collector with gravel inside the tabular solar still increased the freshwater production by 14.18%. Dawood *et al.* (2020) applied an evacuated tube on the focusing line of a parabolic trough collector and a serpentine heat exchanger with an under-basin phase change material. They used oil, water, and nano-oil as working fluid around the evacuated tube and the serpentine heat exchanger, and achieved 28% higher performance than a conventional solar still. Abdullah *et al.* (2021) fabricated a solar still with rotating wick belt and tested its performance. Their results showed an increase in productivity of up to 300%.

A review of former research works indicates that the simultaneous effects of flat external reflectors and trough solar collectors have not been investigated yet. So, in this research, we have tried an experimental study of the simultaneous effects of flat external reflectors and parabolic trough collectors on the efficiency and performance of a stepped solar still. Using both of these mechanisms simultaneously can be more effective in enhancing a solar still's efficiency; because in this technique, the reflectors increase the amount of solar energy received by the steps of the still unit and also by the parabolic trough collector, and this enhances the performance of the collector as well. For this purpose, a solar still has been designed, built and subsequently subjected to different tests under ambient conditions. In this research, the effects of both mechanisms on the performance of a stepped solar still have been investigated experimentally. The two mentioned mechanisms have been applied separately as well as simultaneously. Testing an actual stepped solar still under ambient conditions leads to more credible results because all the parameters that influence the performance of the system play an active role. Figure 1 shows the schematic of the solar still system designed and built in this research.

2. METHODS

The experimental model built for this research includes a one-way stepped solar still, a parabolic trough solar collector consisting of a small-size evacuated glass tube, and a semi-cylindrical mirror under the vacuum tube and two flat reflectors above and below the still unit. The two reflectors used in this system increase the amount of solar energy received by the steps and the trough collector of the system. There is a storage tank of saline water behind the still, which is connected to the evacuated glass tube. The saline water discharged from the storage tank is preheated by the evacuated glass tube before entering the

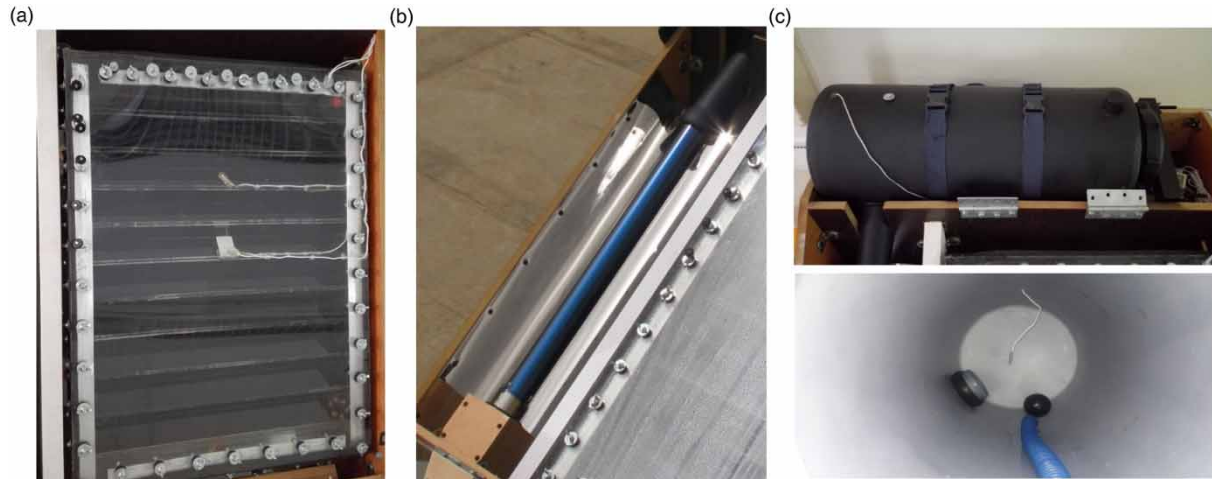


Figure 2 | A view of (a) the stepped solar still system, (b) parabolic trough collector, (c) saline water storage tank (top) and the equipment used inside the saline water tank (bottom).

Table 1 | Thermo-physical properties for different components

Component	Thickness (mm)	Conductivity (W/m-K)	Specific heat (kJ/kg°C)	Density (kg/m ³)
Glass and absorber	3	0.18	0.35	1,180
Insulation	30	0.033	1.3	1,050

steps. In fact, the evacuated glass tube continually preheats the water inside the storage tank. This saline water continually circulates through the vacuum tube, and after being heated there, returns to the storage tank via a natural convection process. All the mechanisms have been installed on a wooden framework, and an attempt was made to make the still unit as compact as possible. The examined solar still is kept in the South alignment during testing in order to receive the greatest amount of solar energy. Each constituent component of this solar still unit has been described below.

2.1. The stepped solar still

The still system designed and constructed in this research is a stepped solar still made of Plexiglas. This unit has 10 steps for the conveyance of saline water and one step at the end for collecting distilled water. The tread of each step has an area of $50 \times 5 \text{ cm}^2$ and its rise (height) is 3.5 cm. The total area of step treads is 0.25 m^2 . For absorbing more of the sun's energy, the steps used for the conveyance of saline water are coloured black, while the other areas are totally transparent. Although the best material for step treads is aluminium (Panchal & Shah 2010) since those surfaces should be painted black to absorb more of the sun's energy and it is likely that aluminium will corrode and paint will dissolve slightly in water in the long term, black-coloured Plexiglas has been used in this research for step treads. Since the surface of the step treads is opaque, the transmittance is negligible. The saline water-conveying steps have been insulated from underneath with 3 cm-thick Styrofoam in order to minimize the amount of heat loss in them. The top cover of the still unit is transparent Plexiglas, and it has been installed and made water-tight by means of nuts and bolts. This allows the top cover to be removed for the periodic cleaning and servicing of steps. The 3 mm-thick top cover has been inclined at 35° , proportional to the latitude of Karaj city (35°N , 51°E). Saline water is discharged through a valve onto the first step, and the residual brine is removed from the last step via another valve. Also, distilled water is collected from the step on which it accumulates through a third valve. The saline water to be desalinated is stored in a 25-liter storage tank behind the solar still. The parts of the stepped solar still examined in this research have been depicted in Figure 2. Thermo-physical properties for different components are mentioned in Table 1.

2.2. Parabolic trough collector

A small evacuated glass tube is used to preheat the saline water in the storage tank. This vacuum tube, which is situated next to the steps, is connected to a saline water tank behind the solar still and has the same slope as the top cover over the steps. To



Figure 3 | A view of the solar still system manufactured and tested in this research.

enhance the still's efficiency and increase the amount of received solar energy, a semi-cylindrical polished stainless-steel sheet of 20 cm diameter has been installed underneath the vacuum tube. The vacuum tube and steel sheet have been inclined at 35° horizontally. A view of this parabolic trough collector is shown in [Figure 2\(b\)](#).

By using the parabolic trough collector, the saline water in the storage tank is heated through the process of natural convection, and the water in the upper part of the tank is always warmer than the water in its lower region. So, a floater along with a soft extendable hose is used to continually draw warm saline water from the top portion of the storage tank. The saline water storage tank and the equipment inside it, including the floater and the extendable hose, the connecting line to the evacuated glass tube, and the temperature sensor, have been depicted in [Figure 2\(c\)](#).

2.3. Flat external reflectors

Two glass mirror-type flat external reflectors have been installed at the top and bottom of the examined solar still. These two reflectors increase the amount of solar radiation received by the steps and the trough collector, and their angles can be adjusted according to different seasonal requirements.

2.4. The complete solar still model built for this research

All the components of the designed and manufactured stepped solar still have been installed on a fixed platform, and we have tried our best to have a compact unit with an integrated structure. A view of the solar still designed and built in this research has been illustrated in [Figure 3](#).

Table 2 | Specifications of measuring devices

Device	Measurement interval	Accuracy
Pyranometer	0–4,000 W/m ²	± 5 W/m ²
Graduated cylinders	0–1,000 ml	± 10 ml
Digital thermometer	–5 °C to + 180 °C	± 1 °C
TDS meter	0–2,000 ppm	± 1 ppm

3. THE OPERATION OF THE EXAMINED STEPPED SOLAR STILL AND THE TEST PROCEDURES

The front edge of each step on which saline water flows has a protrusion, and there is a small empty space at the far end of each step tread for receiving and transferring water to the next step. This empty space has been repeated every two steps. First, the saline water from the storage tank enters the first step and then flows over succeeding steps in a zigzag fashion. This gives the water more time to flow over the steps and be heated by sunlight, so its temperature gradually increases. Sunlight heats up and evaporates the water flowing over the step surfaces. This water vapor gradually condenses underneath the top cover of the solar still, and the distilled water drops then roll down the top cover and are collected on the last step. In the next step, the condensed water is collected from the last step and poured into a special container. The residual brine is also removed from the last step and conveyed to another container.

During the daytime, the parabolic trough collector gradually heats up the saline water in the storage tank; this raises the temperature of the saline water that enters the solar still and enhances the efficiency of the system. Also, the external reflectors help to boost the amount of solar energy received by the steps and the collector. Two temperature sensors are used to measure the temperature of the step treads and the water flowing over the steps. Another temperature sensor has been installed on the top cover of the steps, and a fourth sensor is used to measure the temperature of saline water inside the storage tank. Each of the sensors is connected to an LCD module, and the temperature is manually read and recorded through these monitors. A graduated cylinder is used to gauge the volume of the distilled water produced by the solar still. The flow rate of inlet saline water is inversely related to the volume flow rate of distilled water produced (Tabrizi *et al.* 2010). So in all the tests performed in this research, the discharge valve of the saline water storage tank has been adjusted to obtain the least possible flow rate (30 ml/min) for the inlet saline water. Considering the spring season and the test location latitude of 35°, the tilt angles of the top and the bottom external reflectors were set to their optimal values (10° and 45° relative to vertical and horizontal axes, respectively) in the performed experiments (Katabchi *et al.* 2019). The values of solar radiation intensity, distilled water output, temperatures, and produced water TDS were obtained by means of measuring devices. The specifications of the measuring instruments used in this research have been presented in Table 2.

In this research, the performance of the stepped solar still was inspected from 8 A.M. to 5 P.M. The temperatures of step treads, the top cover over the steps, the water flowing on the steps and the saline water inside the storage tank along with the amount of produced distilled water and solar radiation intensity were recorded on an hourly basis. The solar still unit was tested in the city of Karaj for four days (May 23 to May 26) and in four different modes of operation, as follows:

- Simple stepped solar still (Mode A)
- Stepped solar still along with a parabolic trough collector (Mode B)
- Stepped solar still along with flat external reflectors (Mode C)
- Stepped solar still along with a parabolic trough collector and flat external reflectors (Mode D)

In mode A, the trough collector and the flat reflectors were covered in order to solely analyze the performance of the steps. In mode B, only the reflectors were covered in order to examine the performance of steps along with the trough collector. In mode C, the system's trough collector was covered in order to study the performance of steps together with the two flat reflectors. And in mode D, all the components of the stepped solar still including the steps, reflectors and the collector were exposed to sunlight so that the performance of the whole system can be evaluated. In order to validate the obtained results, the tests were repeated several times.

4. GOVERNING EQUATIONS

In order to validate the empirical results, the governing equations of the problem are presented in this section. The energy balance equation for one step tread is expressed as Equation (1) (Kabeel *et al.* 2012).

$$I(t)A_b\alpha_b = m_b C_{pb} \left(\frac{dT_b}{dt} \right) + Q_{c,b-w} + Q_{loss} \quad (1)$$

In this equation, I , A , α , m , C_p , T , Q_c and Q_{loss} represent the solar radiation intensity, surface area of steps, step absorptivity, step mass, the specific heat capacity of steps, step temperature, amount of convection heat transfer, and the amount of heat loss in the solar still, respectively.

The energy balance equation for the saline water entering the solar still is expressed as (Kabeel *et al.* 2012):

$$I(t)A_w\alpha_w + Q_{c,b-w} = m_w C_{pw} \left(\frac{dT_w}{dt} \right) + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} + Q_{fw} \quad (2)$$

where Q_{fw} , $Q_{e,w-g}$ and $Q_{r,w-g}$ denote the heat transfer of inlet saline water, evaporation heat transfer of water and the radiation heat transfer between water and Plexiglass, respectively.

The energy balance equation for the top cover of the stepped solar still is defined as Equation (3) (Kabeel *et al.* 2012).

$$I(t)A_g\alpha_g + Q_{c,w-g} + Q_{r,w-g} + Q_{e,w-g} = m_g C_{pg} \left(\frac{dT_g}{dt} \right) + Q_{r,g-sky} + Q_{c,g-sky} \quad (3)$$

The hourly distilled water output of the still system is written as (Kabeel *et al.* 2012):

$$\dot{m}_{ew} = h_{e,w-g}(T_w - T_g) \times \frac{3,600}{h_{fg}} \quad (4)$$

where h_e and h_{fg} are the evaporation heat transfer coefficient and evaporation enthalpy, respectively.

The amount of heat transfer between steps and water is obtained from Equation (5) (Kabeel *et al.* 2012).

$$Q_{c,b-w} = h_{c,b-w} A_b (T_b - T_w) \quad (5)$$

In the above equation, h_c denotes the coefficient of convection heat transfer between steps and water, which is considered about 135 W/m^2 (Kabeel *et al.* 2012).

The amount of heat loss from the bottom and sides of the still unit to the surroundings is calculated according to Equation (6).

$$Q_{loss} = \left(\frac{K_i}{L_i} \right) (A_b + A_s) \times (T_b - T_a) \quad (6)$$

In this equation, K_i and L_i represent the conduction heat transfer coefficient and the thickness of the insulating material, respectively.

The amount of heat transfer between water and glass is obtained from:

$$Q_{c,w-g} = h_{c,w-g} A_w (T_w - T_g) \quad (7)$$

where the convection heat transfer coefficient is computed by Equation (8) (Kabeel *et al.* 2012).

$$h_{c,w-g} = 0.884 \left[(T_w - T_g) + \frac{(P_w - P_g)(T_w + 273.15)}{268,900 - P_w} \right]^{1/3} \quad (8)$$

In the above equation, P_w and P_g indicate pressure.

The amount of radiation heat transfer between glass and the floor of the solar still is obtained from:

$$Q_{r,w-g} = \sigma \varepsilon_{wg} A_w [(T_w + 273.15)^4 - (T_g + 273.15)^4] \quad (9)$$

where σ and ε denote the Boltzmann constant and the emission coefficient, respectively. The emission coefficient is determined by the following equation:

$$\varepsilon_{w-g} = \left(\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1 \right)^{-1} \quad (10)$$

The amount of heat transfer between water and glass is computed from Equation (11).

$$Q_{e,w-g} = h_{e,w-g} A_w (T_w - T_g) \quad (11)$$

In the above equation, $h_{e,w-g}$ is the coefficient of convection heat transfer between water and glass and is obtained from Equation (12) (Kabeel *et al.* 2012).

$$h_{e,w-g} = 16.237 \times 10^{-3} h_{c,w-g} \frac{(P_w - P_g)}{(T_w - T_g)} \quad (12)$$

The amount of heat received by the saline water in the storage tank is calculated from Equation (13).

$$Q_{fw} = m_w C_w (T_a - T_w) \quad (13)$$

The amount of radiation heat transfer between glass and sky is obtained from Equation (14).

$$Q_{r,g-sky} = h_{r,g-sky} A_g (T_g - T_{sky}) \quad (14)$$

The radiation heat transfer coefficient in the above equation is computed as:

$$h_{r,g-sky} = \varepsilon \sigma \frac{[(T_g + 273)^4 - (T_{sky} + 273)^4]}{T_g - T_{sky}} \quad (15)$$

$$T_{sky} = T_a - 6 \quad (16)$$

The amount of convection heat transfer between glass and the sky is obtained from Equation (17) (Kabeel *et al.* 2012).

$$Q_{c,g-sky} = h_{c,g-sky} A_g (T_g - T_{sky}) \quad (17)$$

The convection heat transfer coefficient in the above equation is computed as:

$$h_{c,g-sky} = 2.8 + 3V \quad (18)$$

where V is the wind velocity.

The daily thermal efficiency of the solar still is calculated from Equation (19) (Kabeel *et al.* 2012).

$$\eta_d = \frac{\sum \dot{m}_{ew} h_{fg}}{\sum AI(t)} \quad (19)$$

In the above equation, $I(t)$ is the solar radiation intensity on an inclined surface, and it is calculated by Equation (20).

$$I(t) = I_b + I_d \quad (20)$$

In the above equation, I_b and I_d represent the direct solar radiation intensity and diffused solar radiation intensity, respectively, and are obtained from Equations (21) and (22) (Tabrizi *et al.* 2010).

$$I_b = S_c \tau_b \cos(\theta) \quad (21)$$

$$I_d = S_c \tau_d \cos(\theta) \quad (22)$$

In these equations, S_c , τ_b , τ_d , and θ respectively indicate the solar constant, direct solar radiation constant, diffused solar radiation constant, and the angle of incidence (Tabrizi *et al.* 2010). The angle of incidence is obtained from:

$$\cos(\theta) = \cos\delta\cos(\varphi - \beta)\cos\omega + \sin\delta\sin(\varphi - \beta) \quad (23)$$

where δ , φ , ω , and β are the deviation angle, latitude, solar clock angle, and the slope of the inclined surface, respectively.

Empirical temperature data have been used to theoretically obtain the distilled water output of the examined still unit. The temperatures of step treads, water flowing over the steps and Plexiglas are inserted into the relevant equations, which are solved to yield the distilled water output and the thermal efficiency of the solar still. These values are then compared with empirical data. A computer program written in MATLAB software has been used to perform these computations.

5. RESULTS AND DISCUSSION

The results obtained by testing the designed and built solar still have been presented in this section. In the first step, to validate the empirical results, they have been compared with analytical results.

5.1. Validation

In this section, by using the governing equations, the amount of distilled water produced and the efficiency of the solar still have been computed for the conventional solar still. The theoretical and the experimental hourly efficiencies of the solar still in mode A (the conventional solar still) have been compared in Figure 4(a). The error bar is drawn for $\pm 15\%$ in this figure. As is observed, the efficiency of the system in the early hours of the day is negligible, but it gradually increases throughout the day. In the performed test, because of the existing ambient conditions, the still did not produce any distilled water until 10 A.M., and its efficiency was considered as zero until that time. In the remaining hours, there was a good agreement between theoretical and experimental results and the solar still unit achieved its highest efficiency at the ending hours of the day, both in theory and experiment. The average error obtained for system efficiency is 9.43%.

In Figure 4(b), the theoretical and the experimental water production per unit area by the stepped solar still in mode A have been compared. In both experiment and theory, the distilled water output from the still increases at first, reaches its maximum value at 2 P.M. and then gradually diminishes during afternoon hours. The existing discrepancies between theoretical and experimental results arise from the ambient test conditions (the difference between the computed solar radiation intensity and its actual value), changes in wind velocity, the sky becoming cloudy for short periods, and also from the operating error of the solar still itself. The average error obtained for the system's distilled water output is 13.95%.

5.2. Experimental test results

An important parameter with a great influence on the performance of a solar still is solar radiation intensity. The hourly solar radiation intensities during test days have been illustrated in Figure 5(a) for the solar still operating modes of A, B, C and D. These data have been obtained by means of a pyranometer instrument. The four test days were completely sunny. As the diagram shows, solar radiation intensity steadily rises from the early morning hours, reaches a maximum value at noon and then diminishes gradually. During the day, when mode A was being tested, there was a bit of cloudiness at 3 P.M. and, consequently, less solar radiation was received by the solar still; and this event has been indicated by the diagram as well. Since the four test days were consecutive, the amount of solar irradiance on these days was almost the same. Figure 5(b) shows the variation of both ambient temperature and wind speed during test days. According to the figure,

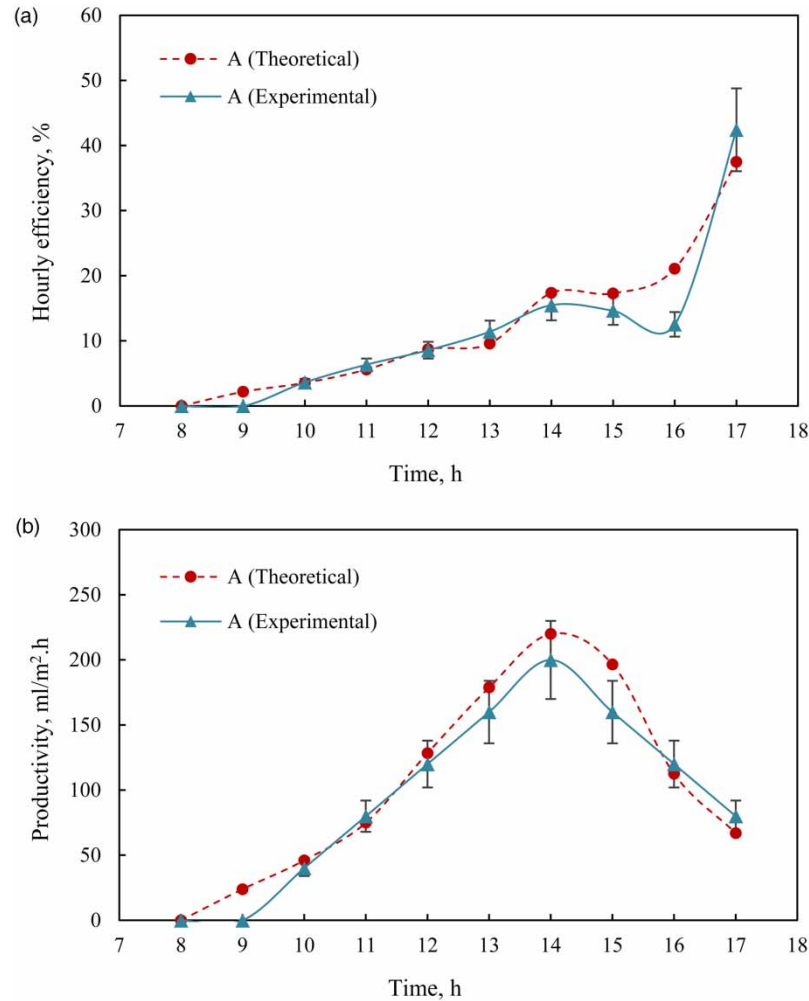


Figure 4 | (a) Comparing the theoretical and the experimental efficiencies of the examined solar still operating in the simple mode, (b) Comparing the theoretical and the experimental water production per unit area by the solar still in its simple mode of operation.

ambient temperature also rises steadily from morning till noon and starts decreasing afterwards. Wind speed, however, has different values during the day and is not predictable.

Figure 6(a)–6(c) respectively show the temperatures of step treads, the water flowing over the steps and of the top cover installed over the steps in four different modes of operation. The temperature of step treads was measured by means of a sensor installed on the fourth step. This sensor was totally insulated from all sides to prevent its contact with the water passing over the steps. In view of Figure 6(a), in all the considered cases, the step tread temperature rises at first, reaches its maximum value at 2 P.M. and gradually decreases afterwards. The step tread temperature in mode B is always higher than that in mode A. This is caused by the preheated inlet saline water in mode B, which warms the treads of the steps as it flows over them. Results show that the step treads attain their highest temperature in modes C and D. Because of using the flat reflectors in modes C and D, the temperatures of step treads in these two modes are considerably higher than those in the other two modes. Since the temperature of step treads is most affected by the reflectors, the temperature is almost equal in modes C and D. The step temperature in mode D is slightly higher than in mode C due to pre-heating of the inlet water.

For measuring the average temperature of saline water flowing over the steps, a temperature sensor was installed on the fifth step of the examined solar still. This sensor was covered with an aluminium plate in order to prevent its exposure to sun's radiation. Test results indicate that the temperature of saline water flowing over the steps behaves similarly to step tread temperature, and that it is higher in modes C and D. With regards to Figure 6(b), due to the preheating of saline water in mode B, there is a substantial rise in the temperature of water on the steps relative to mode A. In mode C, in

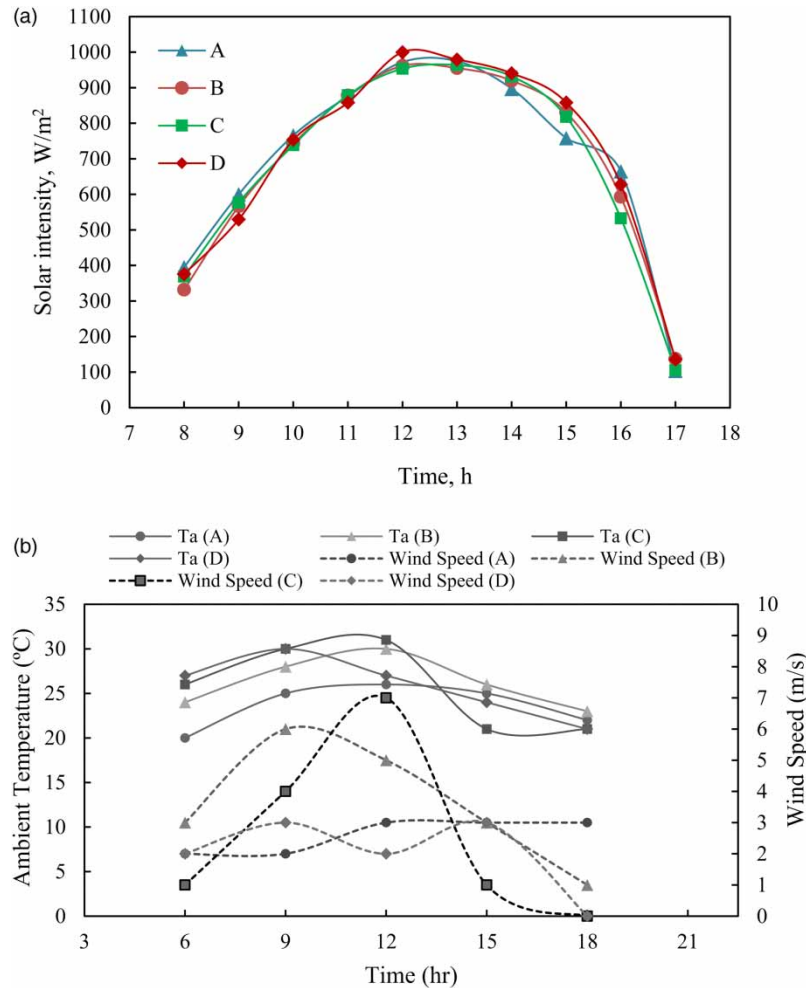


Figure 5 | (a) Hourly solar radiation intensities during test days, (b) hourly ambient temperature and wind speed during test days.

which only the reflectors have been used, the temperature of water flowing over the steps is higher than that in modes A and B. This reveals that the flat external reflectors are more effective in raising the temperature of water flowing over the steps than the trough collector. The highest increase in saline water temperature can be observed in mode D in which the flat external reflectors have been used along with the parabolic trough collector.

To measure the temperature of the top cover over the steps, a sensor has been installed in the middle of this cover and completely insulated on all sides. The cover temperature is almost the same in operating modes A and B. As is shown in Figure 6(c), this proximity of the top cover temperatures can also be seen in modes C and D; because the temperature of the top cover is not much influenced by the solar still's trough collector, and it increases significantly only when the flat reflectors are operated. In all the considered modes, the temperature of the top cover reaches its maximum value at 1 P.M.; since it is not influenced by the still's trough collector, it remains practically the same in modes C and D.

Figure 6(d) illustrates the temperatures of saline water in the storage tank in different modes of operation. These temperatures have been measured by the sensor installed inside the storage tank (see Figure 2(c)). In all four cases, the temperature of saline water continually increases during the day. Part of this temperature rise is due to the direct exposure of the storage tank to the sun's rays, and part of it is due to the operation of the trough collector. As expected, because of using the trough collector in mode B, the temperature of saline water in the storage tank has increased more relative to mode A. Also, in mode D, because of combining the parabolic trough collector with the two flat reflectors, the rise in saline water temperature has reached its maximum value since in this mode, the trough collector is boosted by the reflectors and, therefore, it can raise the temperature of saline water even higher.

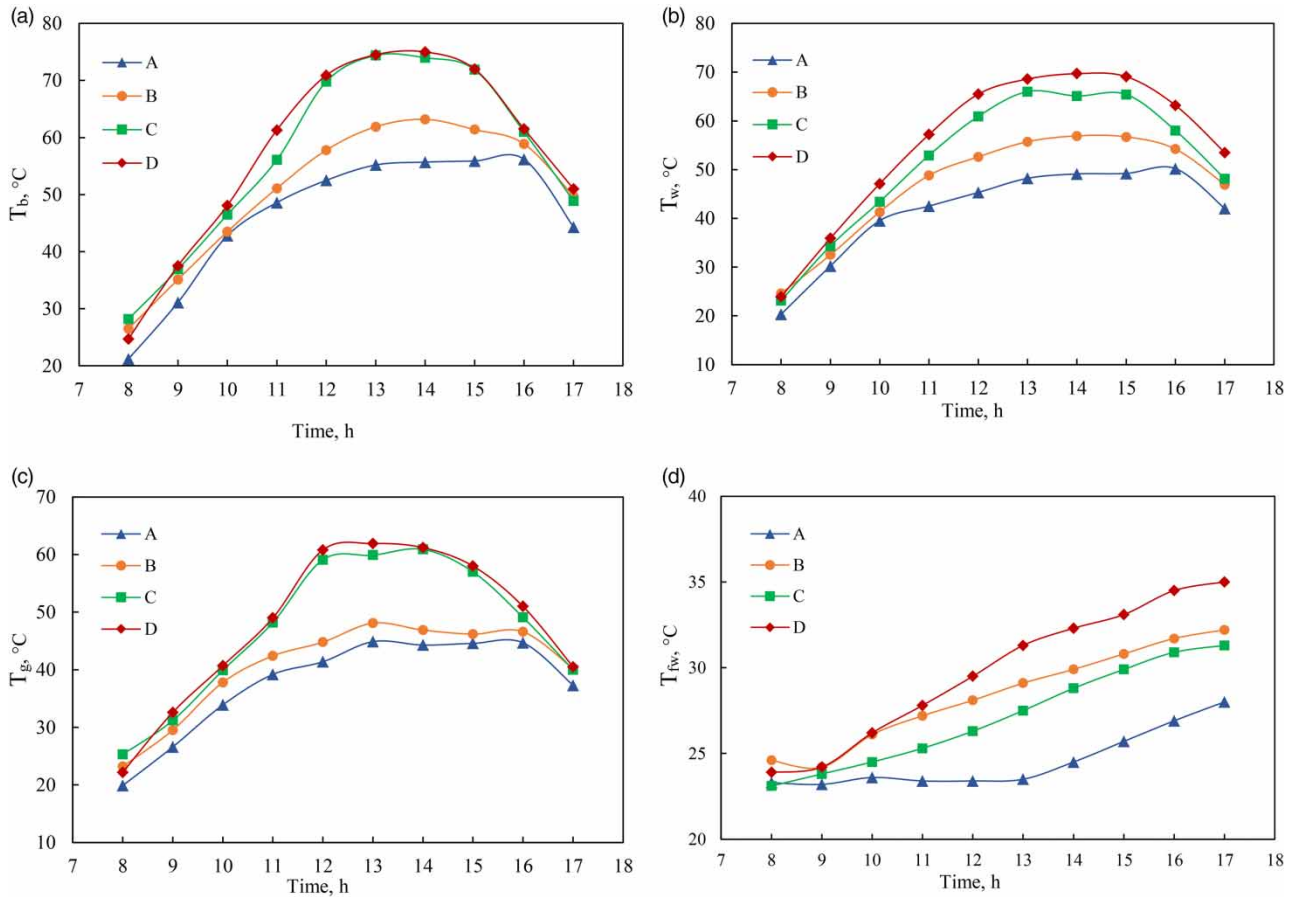


Figure 6 | (a) Temperatures of step treads in the stepped solar still in different modes of operation, (b) temperatures of saline water on the middle step in different modes of operation, (c) temperatures of the top cover over the steps of the examined solar still in different modes of operation, (d) temperatures of saline water in the storage tank in different modes of operation.

The hourly productions of distilled water by the stepped solar still have been shown in Figure 7(a). These quantities have been measured every hour by means of a graduated cylinder. According to this figure, in all the four considered cases, the amount of distilled water produced by the solar still increases initially, reaches its maximum quantity at 2 P.M. and then, with the decline of solar radiation intensity, gradually diminishes. Test shows that the trough collector plays an important role in boosting the production of distilled water. The use of flat external reflectors is even more effective than the trough collector in increasing the amount of distilled water produced. However, the maximum quantity of distilled water is produced when the reflectors are combined with the trough collector in mode D.

The amounts of distilled water accumulated throughout the day have been plotted in Figure 7(b). Here, accumulated water means hourly amounts of produced distilled water successively added together. Similar to Figure 7(a), this diagram also shows that the greatest amount of distilled water is produced by the solar still operating in mode D. The slope of this graph indicates a general increase in the production of distilled water by the solar still, and the sharpest rise in the graph belongs to cases C and D.

Figure 8 shows the TDS values and the electrical conductivities of distilled waters produced in different operating modes. These values have been measured by a TDS gauging device. According to the results, these parameters have much lower values in modes C and D than in modes A and B. This discrepancy could be due to the increase of solar radiation intensity which is achieved by using the flat reflectors and, consequently, raising the temperature of saline water and the steps of the solar still. It seems that the distillation and desalination of saline water at higher temperatures leads to distilled water of greater purity. In other words, by increasing the amount of solar radiation received, the working temperature of the solar still can be raised, and distilled water of lower TDS and EC can be obtained.

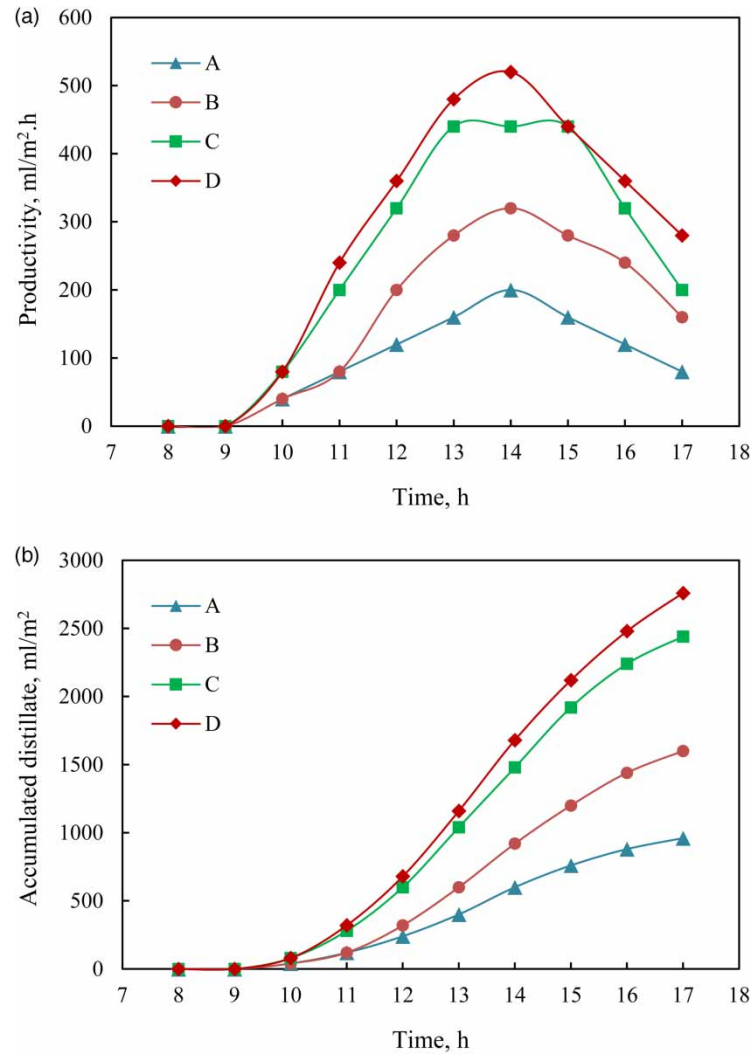


Figure 7 | (a) The water production per unit area in different modes of operation, (b) the hourly amounts of accumulated distilled water in different modes of operation.

5.3. Summary of results

- The effect of using the parabolic trough collector (mode B): by raising the temperature of saline water in the storage tank, the trough collector elevates the temperature of inlet water entering the steps and, thus, boosts the amount of distilled water produced by the solar still. In mode A, the temperature of water in the storage tank reaches 28 °C at the end of the day. By using the trough collector in mode B, the saline water temperature is raised to 32.2 °C. This causes the temperature of water flowing over the steps to increase from 49.1 °C (its maximum value in mode A) to 56.9 °C. As a result, the amount of distilled water produced by the solar still goes up from 760 ml/m²/day in mode A to 1,560 ml/m²/day in mode B, which is an increase of 105.26%.
- The effect of using two flat external reflectors (mode C): Research shows that external reflectors are more effective than the trough collector in enhancing the efficiency of the solar still on this scale. The results indicate a rise of maximum step tread temperature from 55.2 °C in mode A to 74.4 °C in this mode. Also, the maximum temperature of water on the steps has reached 66 °C, which is higher than that in mode B. The positive effect of this optimization scheme on distilled water productivity is also evident. The daily production of distilled water has reached 2,440 ml/m², which shows an increase of 194.73% relative to mode A.

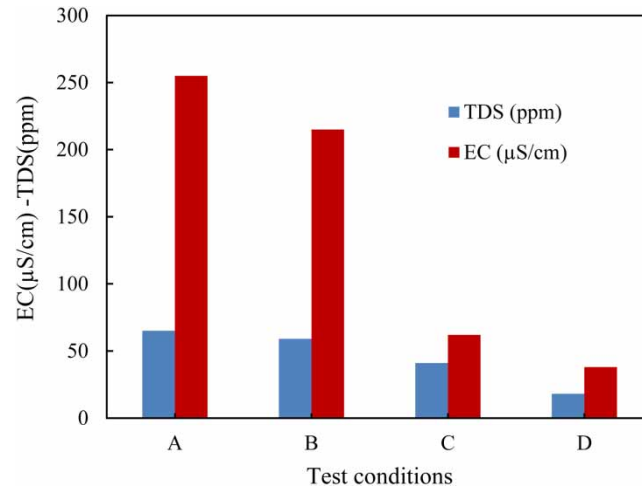


Figure 8 | The properties of distilled waters produced under different test conditions.

Table 3 | Stepped solar still output in different modes

Test condition	A	B	C	D
Maximum step temperature (°C)	55.2	63.2	74.4	75
Maximum water temperature (°C)	49.1	56.9	66	69.7
The maximum water temperature of the saline water storage tank (°C)	28	33.2	31.3	35
Maximum water output per hour (ml/m ² ·h)	200	320	440	520
TDS of water output (ppm)	65	59	41	18
EC of water output (μS/cm)	255	215	62	38
The distilled water produced daily (ml/m ² /day)	760	1,560	2,440	2,760
The additional percentage of distilled water produced (%)	–	105.26	194.73	263.15

- c) The effect of using both the trough collector and the flat external reflectors (mode D): the examined stepped solar still achieves its highest efficiency in this mode of operation. The flat external reflectors not only increase the amount of solar energy received by the steps of the still unit but also by the parabolic trough collector, thereby raising the temperature of saline water in the storage tank, relative to mode B. In mode D, the maximum temperatures of saline water in the storage tank, step treads and of the water flowing over the steps reach 35, 75 and 69.7 °C, respectively; which are higher than those in modes A, B and C. Also, the amount of distilled water produced in this mode is 2,760 ml/m²/day, an increase of 263.15% relative to mode A.
- d) Comparing different modes of operation: the daily amounts of distilled water produced by the examined stepped solar still in different modes of operation have been compared in [Table 3](#).

5.4. Cost evaluation

It is important to produce fresh water at minimum cost. The device costs \$185 to build. The device is estimated to cost \$20 per year and have a useful life of 10 years. So, the total cost of the device for ten years is \$385. On the other hand, it is assumed that the device works 300 days a year. According to the average daily freshwater output, which is 2.5 litres, the total amount of freshwater produced by the device for 10 years is equal to 7,500 litres. As a result, the cost of water produced per litre is equal to \$0.051.

6. CONCLUSIONS

In this research, two optimization schemes were carried out on a simple stepped solar still unit. First, a parabolic trough collector was employed to preheat the inlet saline water entering the still, and then two flat external reflectors were designed,

built, and tested above and below the still to boost the amount of solar energy received by the steps and the trough collector of the system. In optimizing the still system we avoided using any mechanical devices (e.g., pumps, etc.) or electrical mechanisms (e.g., PV modules, etc.) and tried our best to have a compact and integrated unit. The still was tested in the city of Karaj (Iran) during the spring season. The effects of each of these two methods on system performance were evaluated separately and simultaneously and the results were compared with those of a conventional solar still. The findings of this research work are as follows:

1. Experimental tests show that the amount of distilled water produced by the stepped solar still increases by using either of the two tested mechanisms (parabolic trough collector and flat external reflectors).
2. By employing a trough solar collector (consisting of a small-size evacuated glass tube and semi-cylindrical reflector), the distilled water output of the still system goes up by 105.26%.
3. Using two external flat glass mirror reflectors increases the amount of solar energy received by the still unit and thus enhances the distilled water production of the system by 194.73%.
4. By combining the parabolic trough collector with the flat external reflectors, the distilled water output of the examined solar still system is enhanced by 263.15%.
5. On this scale, the two flat external reflectors are more effective in raising the temperature of inlet saline water and boosting the distilled water output of the system than the trough collector.
6. Increasing the amount of solar radiation received by the stepped solar still and thus raising its working temperature seem to better purify the distilled water produced by such desalination systems.

DATA AVAILABILITY STATEMENT

All relevant data are included in the paper or its Supplementary Information.

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