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Seawater desalination using an innovative solar distiller

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ABSTRACT

A simple and workable design of solar distiller (SD) targeted for a household potable water requirement is presented. The efficacy of the SD is tested using seawater taken from the Ad-Dahariz region in Salalah, Oman. The water samples were tested for chemicals and biological activity before and after using the SD. The results revealed that the samples contain different types of minerals in high concentrations and no bacterial activity was found in the samples. After performing the solar distillation, the samples were found in agreement with Omani standards for safe drinking water. The efficiency of the SD among all input volumes and different trials was found to be averaged 11.558% ± 0.370%. The averaged accumulative solar flux (SF) during the test period is 428904 ± 18444 W/m^2. Averaged output/input volume is 8.4709 with a correlation coefficient (R^2) of 0.9999. Averaged % efficiency/input volume is 0.0017 with R^2 of 0.7312. Averaged % efficiency/accumulative SF is 2.0 × 10^{-5} with R^2 of 0.7773. The production of solar distilled water found to be in the range of 1.313–8.625 L/m^2 d. The approximate cost of the prototype is 120 US $. We found that the maximum % efficiency of the SD is 11.856% ± 0.370% obtained when output volume is 694 ± 1 mL, input volume is 6,000 ± 1 mL and accumulative SF is 451,680 ± 1 W/m^2. The proper design of the reflector plays an important role in increasing the efficiency of the SD. The proposed SD is a good tool with minimum investment much suitable for the population of the coastal region.

Keywords: Desalination; Solar distillation; Seawater; Chemical analysis; Biological analysis; Safe drinking water

1. Introduction

Among many renewable energy sources, solar energy is the most important and abundant one. This source can be harnessed by the solar collectors which are of different types including the simple glazed flat plate collector. Due to the simplicity and effectiveness of the glazed type collector design, it has been used for several applications [1]. The solar energy can be converted directly into different types of energy like electricity (pv) and heat (pt). It can be indirectly converted into mechanical work like in water pumping, electricity as in a sterling engine. The heat collected from the sun can be used for different purposes like making chemical reactions and desalination [2].

The desalination is performed either using thermal energy (through the phase-change process) or electricity (driving membrane processes). Desalination by solar-thermal involves several techniques like multistage flash distillation, multi-effect distillation, freeze separation, and solar still techniques [3]. The concentration of solar power is most suitable for large-scale plants that need both high-temperature fluids and electricity. However, solar and wind electricity are very effective resources for reverse osmosis, electrolysis, ultra- and nano-filtration. All these water desalination processes need special operations and their high energy requirements increase the production capacity thus, paving the way for solar and wind to power these applications [3]. Reif et al. [4] use direct solar-desalination systems using solar-thermal collectors which is the most attractive for the optimization of the energy efficiency of solar desalination systems.

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Safe drinking water is the elixir of life and is also the cause of some of the struggles recently. Each person needs at least 2 L of clean water daily for basic survival [4]. The water can be polluted chemically and biologically. There are certain limits of chemicals and biological elements for water to be considered safe internationally [5]. There are several ways that contaminated water can be sterilized and one of them is heat sterilization. Different techniques for solar desalination of seawater are reported in the works of El-Agouz et al. [6], Gude and Nirmalakhandan [7], Liu et al. [8], Schwarzer et al. [5], Palenzuela et al. [9], Mitra et al. [10] and Compain [11]. So, water desalination is becoming a competitive solution for having safe drinking water around the world [12]. In this study, solar energy is harnessed for water sterilization and desalination. The seawater samples are taken from Ad-Dahariz region Salalah, Oman. Then a prototype was designed for solar desalination and water purification. The resultant water becomes very close, in specifications, to the safe drinking water according to Omani standards of safe drinking water.

2. Experiment design

2.1. Design and manufacture of solar distiller (SD) prototype

The solar distiller (SD) prototype was designed as a rectangular shape box (angular solar water still) made from glass. The Parallel rectangles shaped design with length (*L*) 51.5 cm and width (*W*) 30.3 cm. The base dimensions: *L* of 57.0 and *W* of 30.3 cm. The prototype had two separate heights (*H*1) of 25.5 and *H*2 of 41.5 cm. Inside the prototype a small glass in the front act as the condensing part with *L* of 28.0 and *W* of 17.5 cm. An absorber inside the water still was inserted made from a stainless steel plate painted by a black color with dimensions: *L* of 49.5 and *W* of 29.3 cm. In a previous study selective absorber (nickel-pigmented aluminum oxide selective absorber) instead of black paint [13]. The schematic diagram for the prototype for the solar distillation is shown in Fig. 1.

The black bottle contains the seawater sample (input let). The silvery bottle receives the desalinated seawater. The glass box includes the evaporator and condenser (glazed flat plate collector). The aluminum foil represents the reflector. Table 1 shows the specifications of the SD (glazed flat plate collector). The seawater samples were analyzed chemically and biologically before and after the solar desalination process. The efficiency of the SD for the production of pure water was calculated using the input water volume to the output water samples shown in Table 2. It was found that the efficiency without the aluminum foil reflector is low. So, we started the process with the reflector to have high process efficiency.

2.2. Experimental procedure

The seawater sample was taken from the sea near the Ad-Dahariz region of Salalah, Oman. The seawater was slowly poured into the input tank to be distilled. Certain input volume of seawater was introduced at once inside the SD and inlet was closed. The system was closed to entrap the heat and generated vapor. The system was tested under sunshine during the daytime. After sunset, the accumulative condensed water was collected in the output tank as seen in Fig. 2.

Table 1
Specifications of the solar distiller

Total volume (±0.01 cm^3)	52,275.08
Surface area (±0.01 cm^2)	1,959.58
Absorber area (±0.01 cm^2)	1,460.25
Surface area for condensate (±0.01 cm^2)	1,121.10
Surface area of reflector (±0.01 cm^2)	490.00

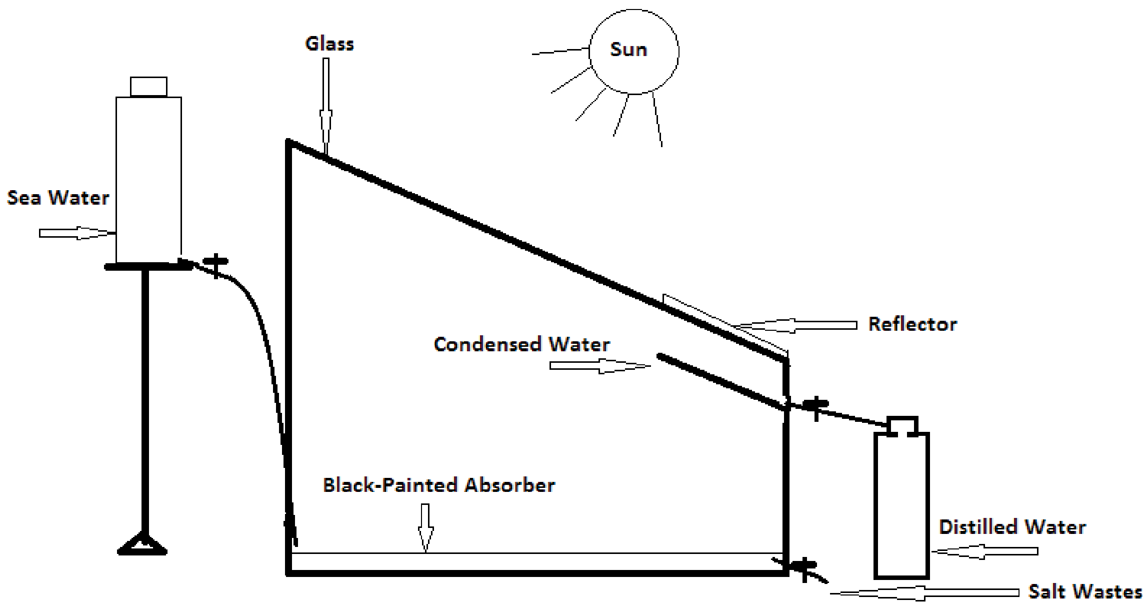

Fig. 1. Schematic diagram for the whole experimental set-up for the solar distillation.

Table 2
Chemical analysis of water before and after solar desalination

Specifications	Before desalination (seawater)	After desalination (pure water)	Standard value
Colour	Colourless	Colourless	Colourless
Odor	Odorless	Odorless	Odorless
pH (±0.01)	6.90	6.00	6.50-8.00
Electrical conductivity (μS/cm) (±1)	53,000	400	240–1,200
Total dissolved solids (mg/L) (±0.1)	52,700	246	120–600
Total hardness (mg $CaCO_3$/L) (±0.01)	36,890	288.00	200–500
Total alkalinity (mg $CaCO_3$/L) (±0.01)	263.30	241.00	Less than 300
Turbidity (NTU) (±0.01)	0.52	0.47	0.00–5.00
Ca^{+2} (mg/L) (±0.01)	438.48	81.12	Less than 100
Mg^{+2} (mg/L) (±0.01)	16.11	20.43	Less than 250
Na^{+} (mg/L) (±0.1)	10,500.0	48.3	Less than 200
K^{+} (mg/L) (±0.01)	500.00	1.50	Less than 10.00
Cl^{-} (mg/L) (±0.01)	20,773.00	2.50	Less than 250
SO_3^{-2} (mg/L) (±0.1)	23.1	0.90	Less than 250
NO_3^{-} (mg/L) (±0.01)	18.42	0.79	Less than 50.00

Fig. 2. Picture of the manufactured solar distiller.

2.3. Cost approximation

All tools and materials (used for making the prototype) were purchased from the local market. The approximate total cost for the system was about 120 US $.

3. Results and discussion

3.1. Chemical analysis

The following tables show the chemical analysis of water before and after solar desalination and their comparison with the specifications of the safe drinking water according to the Omani Standards.

The seawater has high concentrations of minerals as seen from Table 2. There were other studies close to our work. Kale et al. [14] also performed solar distillation of seawater they found the pH of the distillate in the range of 6.8–7.2, while the prototype discussed in this study can obtain water with pH of 6.0 an indication of more purified water. However, Kale et al. [14] reported water without any dissolved solids or ions the purified water produced by our technique we had some dissolved solids and ions as seen from Table 2. Thus, no need for adding the minerals to make it potable according to Omani Standards for safe drinking water.

3.2. Biological analysis

The biological analysis of water samples was done before and after solar desalination is shown in Table 3. The analysis was done in the lab of the Ministry of Defense, Engineering Services, and Civilian Officer Engineer.

3.3. Prototype efficiency and the clean water production rate

The presence of the aluminum foil reflector is very important in doing the desalination process since the percent efficiency is very low without the reflector. The percent efficiency of the SD production rate of pure water was calculated from the input and output volume of seawater samples which is shown in Table 4.

The efficiency is calculated using Eqs. (1) and (2).

$$\text{Efficiency} = \text{output mass/input mass} \quad (1)$$

This can be converted in terms of volume using density (density of seawater 1.025 g/cm^3 and density of distilled water is 1.000 g/cm^3). So, efficiency can be written using Eq. (2).

$$\%\ \text{Efficiency} = 1.025 \times (\text{output volume/input volume}) \times 100\% \quad (2)$$

A certain volume of seawater was introduced inside the SD and the input inlet was closed at the starting of the process (sunrise) till the end (sunset).

Table 3
Biological analysis of water samples before and after solar desalination

Specification	Before desalination (seawater)	After desalination (pure water)	Standard values
Bacteria analysis	Not contaminated	Not contaminated	Not contaminated
Total bacteria colonies (CFU/100 mL)(±1)	NIL	NIL	Less than 1,000
Escherichia coli (CFU/100 mL)(±1)	NIL	NIL	NIL
Total coliforms (CFU/100 mL)(±1)	NIL	NIL	NIL
F. Streptococci (CFU/100 mL)(±1)	NIL	NIL	NIL

Table 4
Calculated average percent efficiency of the solar distiller using different input volumes and different trials

Input volume (±1 mL)	Accumulative solar flux (±1 W/m^2) Trial1	Accumulative solar flux (±1 W/m^2) Trial2	Accumulative solar flux (±1 W/m^2) Trial3	Average accumulative. solar flux (±1 W/m^2)	Output volume (±1 mL) Trial1	Output volume (±1 mL) Trial2	Output volume (±1 mL) Trial3	Average Output (±1 mL)	Average Efficiency (±0.001%)
1,000	430,614	403,496	355,765	396,625	112	105	98	105	10.763
1,500	383,608	391,386	440,246	405,080	155	160	165	160	10.933
2,000	430,188	418,300	393,320	413,936	222	220	218	220	11.275
2,500	430,757	410,225	403,100	414,694	286	283	280	283	11.603
3,000	413,843	432,838	414,035	420,239	344	346	342	344	11.753
3,500	451,306	443,214	415721	436,747	406	402	398	402	11.777
4,000	439,897	438,553	440,646	439,699	455	460	465	460	11.788
4,500	445,787	447,602	439,575	444,321	518	520	516	518	11.799
5,000	445,159	446,320	444,830	445,436	575	570	580	575	11.788
5,500	437,233	454,653	456,588	449,491	632	636	634	634	11.815
6,000	456,805	450,424	447,811	451,680	696	694	692	694	11.849

Average among all % efficiencies = 11.558 ± 0.370%.
Average among all accumulative SF during the test period = 428,904 ± 18,444 W/m^2.

The solar flux (SF) will affect directly the evaporation of the water inside the SD and which can be measured easily using a pyranometer. The accumulative SF so can be calculated during the day from sunshine till sunset. However, the condensed water was collected accumulatively during the day from sunrise till sunset. But we cannot measure the output energy directly but we can measure instead of the output volume of the solar distilled water which represents the output energy. Therefore, Eq. (2) can be used to calculate the % efficiency.

Three trials were done for each certain input volume. Each trial was done in one day from sunrise till sunset. The accumulative SF was measured and calculated for each day.

According to Table 4, the production rate for solar distilled water was in the range of 1.313–8.625 L/m^2 d. The production rate largely depends on the area of the absorber and the input volume of the seawater. Kathum et al., [15] found the rate of production of the solar distilled water in the range 3.0–7.0 L/m^2 d. Thus, the proposed prototype achieves a higher production rate.

Fig. 3 shows the relationship between the input volume of seawater with the average of the output volume of solar desalinated seawater.

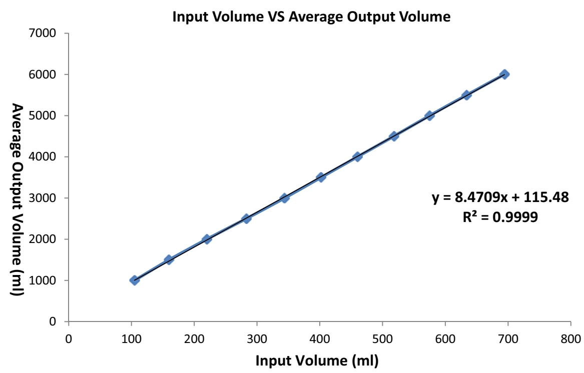

Fig. 3. Relationship between the input volume of seawater and average output volume of pure water.

It was found that as the input volume increases the output volume also increased. This sounds counter-intuitive because evaporation is surface phenomena and the surface area of water is kept constant with increasing input volume. However, as the amount of liquid increases in the chamber, the side area that receives heat from the sun

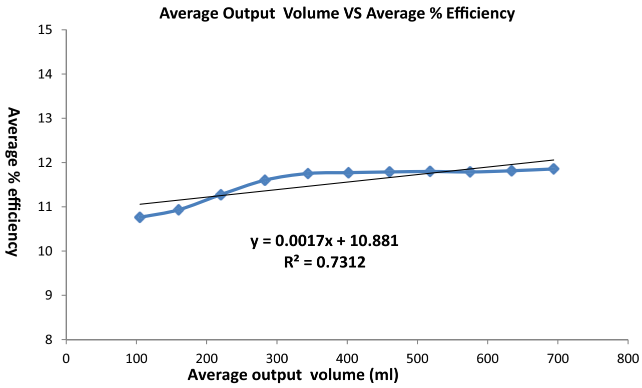

Fig. 4. Relationship between average % efficiency with the average output volume of pure water.

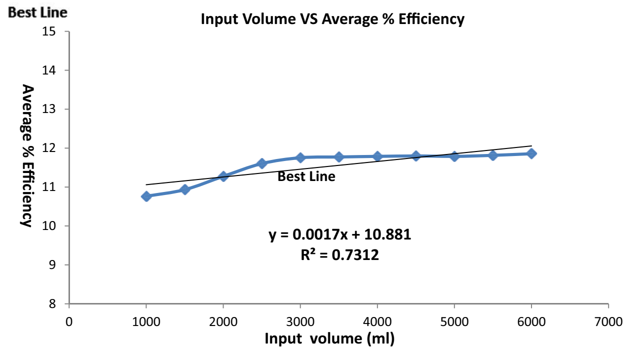

Fig. 5. Relationship between average % efficiency with input volume.

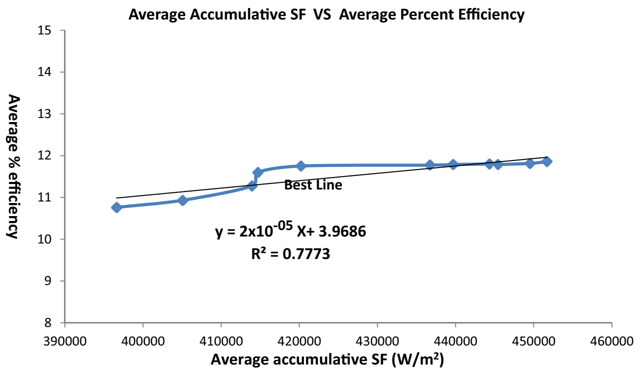

Fig. 6. Relationship between average % efficiency with average accumulative SF.

also increases. This trapped heat contributed to the linear increase of output with input. Since output varies linearly with input efficiency of the system becomes almost flat and reaches a constant number. The averaged output/input volume was found at 8.4709.

The linear equation between the average output volume with input volume is:

$$Y = 8.4709X + 115.48 \qquad R^2 = 0.9999 \tag{3}$$

The linear relationship is very strong as seen from the correlation coefficient (R^2). So we can determine easily the output volume of pure water using certain input volume of seawater (saline water) by applying Eq. (3) directly.

Fig. 4 shows the relationship between average % efficiency with average output volume.

From Fig. 4 the % efficiency is almost constant with output volume. The R^2 shows a linear relationship between the two parameters. The slope is very small (0.0017).

The linear equation between the average output volume with output volume is:

$$Y = 0.0017X + 10.881 \qquad \text{with } R^2 = 0.7312 \tag{4}$$

The same behavior obtained when we took the relationship between average % efficiency with input volume (Fig. 5).

Fig. 6 shows that as accumulative SF increased the % efficiency almost increased and there is a linear relationship between the two parameters with R^2 of 0.7773.

The linear equation between the average % efficiency with average accumulative SF is:

$$Y = 2 \times 10^{-5}X + 3.9686 \qquad \text{with } R^2 = 0.7773 \tag{5}$$

A previous study of different designs of solar still by Hoque et al. [16], gave a production rate of 2.38 L/m^2 d which is very low compared to our prototype.

We found that maximum % efficiency is 11.856% ± 0.370% obtained when output volume is 694 ± 1 mL, input volume is 6,000 ± 1 mL and accumulative SF is 451,680 ± 1 W/m^2.

There are different sources of errors in our study like personal and instrumental errors.

4. Conclusions

The innovative solar desalination prototype (SD) based on a glazed flat plate collector was designed, manufactured and tested on seawater which was taken from the Al-Dhareez region of Salalah, Oman. It was found that the desalinated seawater is in close agreement with the specifications of the safe drinking water prescribed by Omani standards. The average % efficiency of the prototype is 11.558% ± 0.370%. while the production rate falls within the range of 1.313 to 8.625 L/m^2 d. The maximum % efficiency obtained is 11.856% ± 0.370%. The presence of aluminum foil reflector doubled the percent efficiency over the condensing part of the SD.

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