Modeling and Designing of a Novel Lab-scale Passive Solar Still

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Abstract. The solar still is an emerging water distillation technology gaining popularity among the scientific community. Achieving a high throughput and/or performance in solar stills remains an unresolved challenge. In this study, the feasibility of utilizing solar distillation systems for large water production was investigated. A solar still was designed and tested with different brackish waters under solar insolation in Los Angeles from March to April. The inner surface area of the cell was about 12.7 cm × 12.7 cm with a maximum volume of 322.6 cm^3. The still performance was evaluated experimentally and modeled theoretically, showing a good agreement between theory and experiment. The maximum achieved efficiency was 20.54%, corresponding to a freshwater production of 384.4 mL/day·m^2 (6.2 mL/day). Lowering the feed amounts from 120 to 30 mL/day resulted in increasing the experimental performance from 6% to 18.3% due to the quick ramp in heat of vaporization; however, the production rates decreased from 446.4 to 341 mL/day·m^2 (7.2 to 5.5 mL/day). Polystyrene insulation and blackened walls/basin can improve the performance by maintaining high temperature, decreasing heat loss, and enhancing solar absorption. It is concluded that still materials, insolation rate, and inclination angle are the most critical design factors.

Keywords: *freshwater; irradiation; solar distillation; solar still; water purification.*

1 Introduction

Water is the most vital element in nature and is required for life activities and other purposes. Ocean water contributes around 97% of the worldwide water [1]. However, only 1% is covered by accessible freshwater sources, which are limited to rivers, lakes and underground reservoirs [1-2]. The world's demand for drinking water has been increasing rapidly since the industrial revolution due to the continuous production of wastewater, which contaminates available freshwater sources [3-5]. Typically, membrane processes are utilized for the treatment of industrial wastewaters in micro and ultrafiltration processes, and for desalination of seawater by reverse osmosis to meet the increasing demand for freshwater [3, 6-8].

Received August 11th, 2018, 1st Revision February 25th, 2019, 2nd Revision March 29th, 2019, Accepted for publication April 1st, 2019.
Copyright ©2019 Published by ITB Journal Publisher, ISSN: 2337-5779, DOI: 10.5614/j.eng.technol.sci.2019.51.3.1

Conventional water distillation processes require high energy input from either electric and/or fossil fuels as power source to produce freshwater. However, solar energy is free, renewable and environmentally friendly and can be easily employed for seawater desalination and industrial water purification applications. Solar desalination systems can be divided into direct and indirect collection methods. Direct systems utilize sun energy directly as thermal energy to evaporate water, while indirect systems use solar radiation to produce electricity that is consequently used in water distillation. A solar still is a potential direct solar desalination system that exposes a shallow water basin inside a fully closed container to solar radiation in order to evaporate water. Water vapor condenses on the still inner top side, a transparent cover that is usually made of Plexiglas, due to the developed temperature gradient between the water and the still cover temperature [9-11]. The solar water distillation process depends on the principle of condensation and evaporation of water, replicating nature in rain events [1,12]. In other words, a solar still heats water to the point of evaporation; then water vapor rises and condenses on the tilted glass surface for collection. Solar stills are capable of removing contaminants such as salts, heavy metals, and toxic organics to produce fresh and very clean water [1].

A solar still consists of the following components: (i) a feed-side inlet, an absorber plate (basin) in which brackish or saline water is placed, (ii) a tilted glass cover, (iii) a frame that is either glass, plastic or metal, (iv) a glass partition to separate the feed side from the distillate side, and (v) a distillate-side outlet channel for water collection [12-14]. Numerous factors may have an impact on the performance and productivity of a solar still, including, but not limited to, solar intensity, wind velocity, ambient temperature, difference in water-glass temperature, free surface area of water, absorber plate area, feedwater temperature, glass cover angle, and depth of water correlated with feedwater flow rate in mL/day [12].

The two major classes of solar distillation systems (solar stills) are passive and active solar stills. Passive systems are closed and not connected to other operations, whereas active solar systems are integrated with other processes for achieving high performance viability. Every class has various subclasses based on the chosen design for the solar still. For example, a conventional passive solar still design is constructed with a single-slope or a double-slope glass cover. Both designs operate at low temperatures (< 60 °C). However, the single-slope design is known to be more versatile and efficient than the double-slope design, as reported in previous works [1]. Rajaseenivasan and Murugavel [15,16] have conducted a solar still experiment on a double-slope single basin and a double-slope double basin, and found that providing an additional basin increased still productivity by approximately 85%.

Introducing a small-scale household desalination system powered by renewable solar energy has been determined to be possible with a feasible implementation of solar stills in deserted areas [17]. Market analyses have shown that there is a promising potential for small-scale solar systems for seawater and brackish water desalination in remote urban and agricultural areas. However, technical and economic analyses must be conducted to check their commercial feasibility. Further, some pilot plants must be built and run for demo-production to demonstrate the reliability of system operation [18]. In 2017, Burbano [19] revealed that solar stills were capable of desalinating seawater in a sustainable manner for producing potable water in an arid environment in Colombia. The study verified that a community in the desert of Guajira would be able to use local resources and renewable energy, such as solar radiation yielding about 6-6.5 kW/hr/m^2·day, to produce freshwater [19].

A common issue with using solar stills is that a great amount of the collected solar heat is lost within the still components or to the surroundings, resulting in poor still performance [19]. Many attempts have been made by scholars to increase the daily distillate production of solar stills through improving cell insulation and collection capabilities (solar absorption) of solar energy (heat). A good technique to achieve maximum performance is to manipulate the still design parameters, the operating conditions and control environmental factors such as solar intensity, wind speed, weather temperature, humidity, and other climate conditions [12].

To date, several studies have been done in an attempt to increase freshwater production from solar stills. One previous study enhanced solar still performance by an external solar collector and a phase change material to achieve a highest daily productivity of 4300 mL/day·m^2 with an average total freshwater production of 3735 mL/day·m^2 in the month of August [20]. The performance of both single- and double-basin solar stills (with an inner surface area of approximately 90 cm × 50 cm for each still) was experimentally investigated in an insulated-side reservoir, which showed a production capacity of 1280 and 1760 mL/day, respectively [21]. Another study tested single-basin and double-basin solar stills fabricated with a tilted glass cover at 12° and 36°, respectively, with a basin size of 0.9 m × 0.7 m × 0.008 m (volume ≈5040 cm^3), which showed a higher production rate of 1330-1940 mL/day for the single-basin still and 2605-3580 mL/day for the double-basin still, owing to the higher volume and/or surface area provided in the designed basins, giving more opportunity for radiation absorption and water evaporation [22].

Bait, *et al.* [23] and Morcos [24] suggested an embedded double-slope solar still with a solar-heating system (collectors) to ensure high heat absorption and contribute to maintaining a higher basin water temperature than the observed temperature in simple stills, showing a maximum theoretical modeled daily production capacity (cumulative yield) of ∼4 kg/m^2 (4000 mL/day·m^2). A circular tube with high glass crystallinity may be utilized to contain the heating coils and/or PV thermal collectors [25], thus absorbing more solar energy due to high glass absorptivity and emissivity [26] while preventing heat to escape owing to low glass reflectivity [23].

Moreover, another recent theoretical study on active stills by Bait [27] investigated a tubular solar collector assisted solar still for the removal of salt from contaminated water. The designed hybrid system consisted of a single-stage desalination system (double-slope basin) connected to a tubular solar heater (blackened coil tube) [26]. The solar basin was coated with black paint to improve solar absorption. Exergy analysis revealed that evaporative flux dominates both convective and radiative fluxes for conventional and hybrid-modified solar stills. The rate of evaporation largely increased with the integration of solar collectors with the still basin to have an annual yield of ∼549.77 kg/m^2 (1506.21 mL/day·m^2) as compared to a conventional still with an annual yield of ∼405.04 kg/m^2 (1109.67 mL/day·m^2) [27]. Mutasher, *et al.* [28] tested a PV sun-tracking system for use as a solar collector for single-slope stills. The system was capable of enhancing water temperature within the still basin, resulting in higher efficiencies for both passive and active solar stills, at 22.7% and 38.55%, respectively.

A review study by Bait [29] highlighted the importance and the role of using nanofluids with particle size ranging from 1 to 100 nm for solar energy desalination technologies such as solar stills. Promising metal and metal oxide nanoparticles (arranged from low to high thermal conductivity) are titanium dioxide (TiO_2), copper oxide (CuO), alumina (Al_2O_3), graphene oxide (GO), carbon nanotubes (CNTs), and silicon dioxide (SiO_2) with thermal conductivities of 8.4, 33, 40, 1000, 3007.4, and 3970 W/m·K, respectively. Nanoparticles assist in the enhancement of thermal conductivity of water for improved solar absorption and higher evaporation rates. Elango, *et al.* [30] added Al_2O_3 nanomaterials, which increased the water production rate from 100 to 160 mL/h from 12 pm to 2 pm local time. In an experimental study by Ankoliya and Modi [31], Al_2O_3 nanoparticles were added to the feedwater prior to entering into a single-slope double-basin solar still for seawater desalination, achieving a yield of 49% higher than feedwater without nanoparticles. Enhancement of the still yield (thermal entropy generation) may also be achieved via increasing the nanofluid volume fraction with a maximum increase rate of 25%. Hence, nanoparticle size, shape, and amounts have to be taken into consideration for optimal stability and dispersion of nanoparticles in the still basin [29].

In the present work, a small passive solar still was designed from scratch, using available and inexpensive materials, in an attempt to analyze the feasibility of constructing an efficient solar distillation system for household and/or industrial purification purposes to produce large quantities of freshwater. A preliminary AutoCAD design was obtained before construction of the still. The designed solar still was then utilized in an experimental setup and for performance analysis. Different sample quantities of prepared brackish water were considered in the experimental work, which was conducted in the southern region of Los Angeles, CA (34°01'13.6"N, 118°17'45.1"W) from March to April 2017. The solar still was kept at the same climatic conditions to analyze the effect of different design parameters on the overall treatment efficiency, which was investigated through experimental and theoretical calculations.

2 Design Materials and Parameters

A small single-slope passive solar still was designed with simple and inexpensive materials that were available in workshop stores, to facilitate the use of the solar still technology for industrial and personal use. The suggested solar still tank dimensions in this study were quite small, with a tank volume of around 12.7 cm × 12.7 cm × 2 cm. The solar still was only used to prove and confirm the feasibility of the still for water purification application by checking the maximum possible freshwater production capacity and the overall solar still performance. For simplicity, a rectangular container shape was selected for the solar still design. The purchased design materials were Plexiglas sheet, silicon sealant, construction adhesive, a black rubber pad, aluminum foil, polystyrene foam sheet, black insulation duct tape, and removable neutral putty. The applied location and the purpose of each selected material used in the solar still project are explained and described in Table 1.

Different glass parts were used in the construction of the solar still container for the separation of the feed side from the distillate side. The exact dimensions of the used glass parts and their quantities are shown in Table 2. Two partitions were utilized in the design phase. One partition part was placed at the bottom side (from inside) to get a feed side width of a 12.7 cm (5’’) and to separate the water in the feed side from the water in the distillate side. The other partition was placed on top of the still container to cover half of the distillate side and ensure complete closure of the solar still for prevention of heat escape.

The other design parameters, such as slope angle, partition rise, and glass/insulation thickness, are shown in Table 3. According to Raikwar [32], it is common to design passive solar stills with a single-slope inclination of either 23° or 30°, which is supposed to maximize the energy capture as well as the freshwater production rate. Kumar, *et al.* [9] showed that still performance at a

30° inclination increased by about 1.5% as compared to using a 23° angle slope. However, a slope angle of 20° was selected in the design of the solar still in this paper, to check the production rates in a lower angle case.

Table 1 Applied location and purpose of various selected design materials.

Material	Applied Location	Purpose
Plexiglas sheets	Container walls	Constructs the solar still container sidewalls, bottom (basin) and top covers.
Silicon sealant	Walls joints (from inside)	Seals the joints of the glass sides together (from the inside) to prevent water leakage in the solar still. Note that it is better to use a silicon-based material for long-lasting solar stills.
Construction adhesive	Walls joints (from outside)	Connects the glass sides together (from the outside) and provides more durability and strength to the applied sealant.
Black rubber pad	Basin (bottom); feed side (from inside)	Increases the absorption of solar radiation energy in order to have better performance.
Aluminum foil	Container walls; feed side (from inside)	Reflects sunlight radiation inside the container, hence increasing water temperature and evaporation rate.
Polystyrene foam sheets	Container walls; feed side (from inside)	Increases insulation of the solar still feed side to keep absorbed energy and temperature as high as possible.
Black insulation duct tape	Container walls (from outside); except top side	Decreases heat loss (non-reflective) and increases solar absorption by preventing radiation energy escape.
Removable neutral putty	Around glass cover (top)	Gives flexibility to adjustment of the glass cover (removable) at the top of the container. Closes gaps and open spaces between the cover and the container to reduce energy escape.

Table 2 Assigned dimensions of the different glass parts used in the construction phase.

Part Location	Quantity	Dimensions*
Top-side (cover)**	1	12.7 × 17.78 cm (5’’ by 7’’)
Bottom-side	1	12.7 × 17.78 cm (5’’ by 7’’)
Slope-sides***	2	Length: 19.37 cm (7.6’’); IR: 8.7 cm (3.5’’); AR: 2 cm (0.78’’)
Front-side (low rise)	1	12.7 × 2 cm (5’’ by 0.78’’)
Back-side (high rise)	1	12.7 × 8.7 cm (5’’ by 3.5’’)
Partitions	2	12.7 × 2 cm (5’’ by 0.78’’)

*Glass thickness of 3 mm was not considered here; however it was considered in the AutoCAD views.
**Sealant rubber was added to the glass cover to reach the 12.7 × 18.98 cm and to close any gaps.
***There was a 1-cm bottom-distillate-side-gap filled with sealant; IR: initial rise; AR: angle rise.

Table 3 Selected data and other design parameters of the constructed solar still.

Parameter	Value*
Slope angle	20°
Initial rise	2 cm (0.78’’)
Angle rise	8.7 cm (3.42’’)
Feed/distillate partition rise	2 cm (0.78’’)
Glass thickness	3 mm (0.11’’)
Black rubber pad dimension	12.5 × 12 cm (4.9’’ by 4.7’’)
Black rubber pad thickness	3 mm (0.11’’)
Polystyrene foam sheets thickness	3 mm (0.11’’)
Black insulation duct tape thickness	1 mm (0.04’’)
Distillate drain hole	1 × 0.5 cm (0.04’’ by 0.02’’)

*Note that AutoCAD views show dimensions considering the 3-mm glass thickness.

An earlier experimental work by Conti, *et al.* [33] determined that polystyrene foam sheet is a good insulation material since it has the lowest thermal conductivity among other inexpensive materials (e.g. glass and plastic). Glass and plastics have higher convective heat-transfer coefficients; therefore, polystyrene sheets were selected for the insulation in the design step.

3 AutoCAD Modeling and Still Characterization

The preliminary design of the solar still was developed using the AutoCAD design program. The next step of the design process was the construction phase, in which the solar still was designed and constructed with the purchased materials and parts as mentioned in Table 1.

The inner surface area of the cell is about 12.7 × 12.7 cm and with a maximum volume of 322.6 cm^3. It is important to ensure the correct dimensions of the purchased glass parts (see Table 2) as well as the selected parameters reported in Table 3. Applying these data in the construction phase is critical for a successful installation with no defects that may result in leakage problems. Note that the AutoCAD solar still designs did not include the top glass cover since it was designed to be removable.

Figures 1 to 4 show various AutoCAD views and 3D designs of the constructed solar still. For comparison purposes, the designed prototype used in the experimental work is displayed in Figure 4(b).

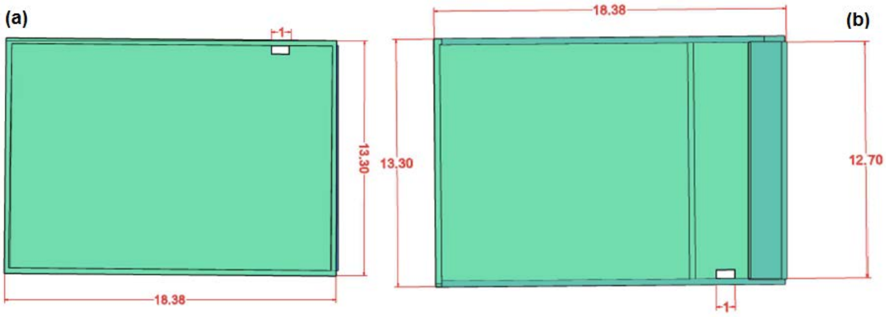

Figure 1 The designed solar still: (a) bottom view, (b) top view.

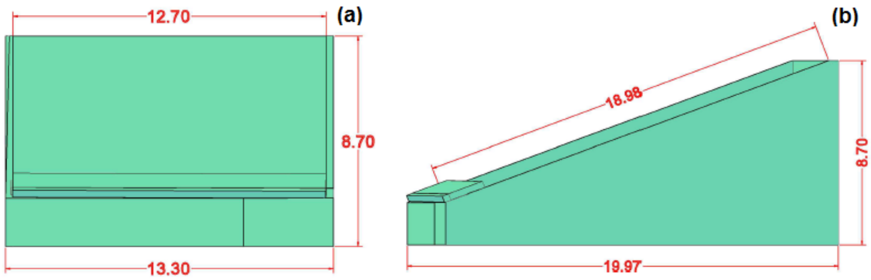

Figure 2 The designed solar still: (a) front view, (b) side view.

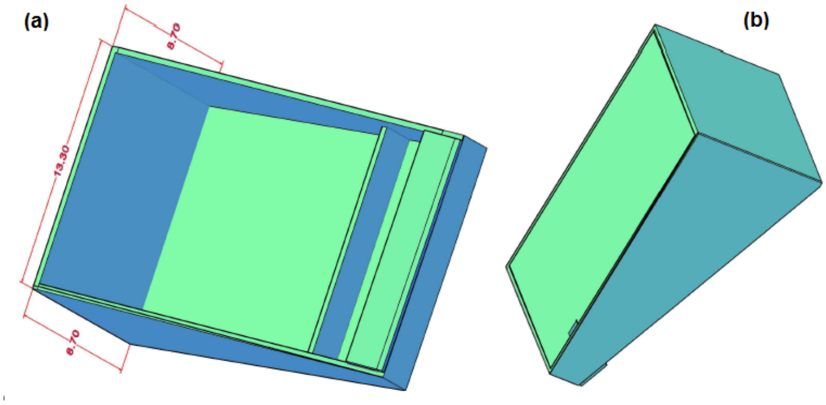

Figure 3 Isometric 3D shapes of the designed solar still showing the principal elements (top, bottom, slope, front, back, and partition glass): (a) 3D reverse side dimensions, (b) 3D reverse side view.

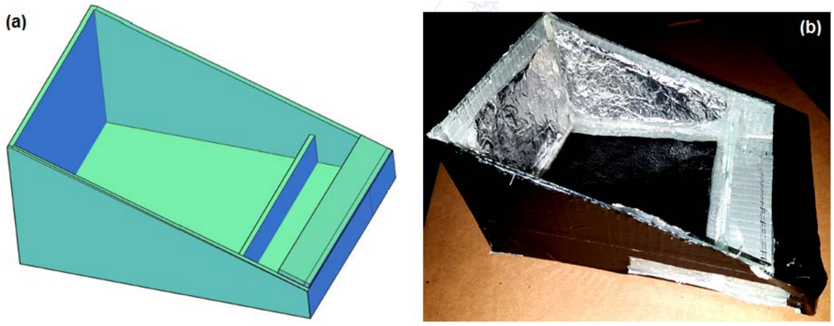

Figure 4 The designed solar still: (a) AutoCAD 3D shape, (b) constructed 3D shape.

4 Experimental Setup

After the construction phase of the solar still container, a leakage test was performed three consecutive times on both the feed side and the distillate side. The solar still was determined to be sealed perfectly and ready for the experiment. Then, the container was placed in an open area (home backyard) in the southern region of Los Angeles, CA (34°01'13.6"N, 118°17'45.1"W). The experiment was conducted in the period of March to April 2017 since the sun's radiation energy (insolation) was then estimated to be at maximum level. The project work was initiated by measuring the effect of solar radiation on the evaporation/condensation rates of different brackish water samples. The solar still was kept under insolation from 9:00 am to 6:00 pm for several days. It should be noted that the brackish water samples were prepared at home to resemble natural brackish water. Gupta, *et al.* [1] reported that the approximate salinity of brackish water should be 0.05-3% based on present dissolved salts, which is equivalent to 1000-80,000 µS/cm [1]. In the present work, water samples resembling brackish water with water inlet (feed) flowrates of 30, 60, 80, and 120 mL/day and an average conductivity of 1075 µS/cm were used as the feed in the experiment.

Water was fed into the system before the installation of the removable glass cover. Since no feed inlet and/or tube was connected to the container, the glass cover was designed to be removable and water was fed into the feed side manually. A removable neutral putty was applied around the glass cover to close any gaps and maintain insulation to prevent heat escape during the experiment (radiation absorption). The water and glass temperatures were measured every hour simultaneously by using two digital thermometers. The greater the difference between glass and water temperatures, the more heat transfer was gotten; thus, higher evaporation and condensation rates were observed. A collection beaker was placed on the distillate side (drain) to collect and measure the purified water in milliliters (mL), so that it would be possible to calculate the still performance for the different feed samples from their corresponding flowrates.

The following experimental measurement tools were used:

1. Two thermometers: to record changes in the glass cover and water temperatures in the daytime during the study period. One thermometer was placed on the glass cover (top side) and the other one was submerged in the feedwater.
2. A milliliter beaker: to measure the exact water volumes of both feed and distillate.
3. A conductivity meter: to identify and check the feed and distillate conductivities.

5 Mathematical Equations and Data

Both the experimental and the theoretical results were considered for the calculation of the designed solar still efficiency. The experimental efficiency was calculated by using two different equations. Eq. (1) is the traditional way to determine the experimental efficiency of any system, whereas Eq. (2) is the instantaneous efficiency equation reported by Kalita, *et al.* and Badran, *et al.* in previous works [10,12]. However, we have made a slight modification to Eq. (2) by introducing a new correction term (depth factor) to accommodate the equation to our small system. Considering the ratio between actual and maximum allowable water levels in the basin, as shown in the added term in Eq. (3), should give us more accurate results for our analysis.

In other words, Eq. (2) calculates the instantaneous efficiency of the system. However, to calculate the overall experimental efficiency, we must adjust the equation using a depth factor. The addition of a depth correction factor results in a new equation, Eq. (3), as proposed by the author. Eq. (3) is capable of estimating the overall experimental efficiency of a single-slope passive solar still with a maximum deviation of 20%. We believe that the suggested equation is only valid for water depth values that are greater than or equal to 1 mm and smaller than or equal to 20 mm (1 mm ≤ H_w ≤ 20 mm). Eq. (3) is more accurate when the maximum possible water depth (H_m) is 20 mm.

$$\eta_{e1} = \frac{D}{F} \times 10 \tag{1}$$

$$\eta_i = \frac{Q \times L}{A \times I} \times 100 \tag{2}$$

$$\eta_{e2} = \frac{Q \times L}{A \times I}\left(\frac{0.75 \times H_m}{H_w}\right) \times 100 \tag{3}$$

The latent heat of vaporization for water can be calculated from Eq. (4) if the operating temperature is below 70 °C [12]. Eq. (4) suggests that higher water temperatures yield low latent heat of vaporization, which indicates that water temperature plays a significant role in increasing still efficiency and productivity.

$$L = 2.4935 \times 10^{6}[1 - 9.4779 \times 10^{-4}\, T_w + 1.3132 \times 10^{-7}\, T_w^2 - 4.7974 \times 10^{-9}\, T_w^3] \tag{4}$$

The heat and mass transfer relationship and the heat balance model for a conventional solar still are analyzed and discussed by the pioneer scholar Dunkle in his famous paper from 1961 [34]. The reported Eqs. (5) to (9) were used in the modeling analysis to determine the theoretical efficiency of the designed solar still. It is clear that the model equations are strongly dependent on both the water and the glass temperature and the difference between them. It was identified that a high-temperature difference increases the heat transfer and condensation rate of the water, which enhances the still performance [1, 9, 12, 34-37]. Table 4 shows the important data that were utilized in our calculations.

$$P_g = exp\left[25.317 - \frac{5144}{T_g}\right] \tag{5}$$

$$P_w = exp\left[25.317 - \frac{5144}{T_w}\right] \tag{6}$$

$$h_{cwg} = 0.884 \times \left[\left(T_w - T_g\right) + \left\{\frac{(P_w - P_g)}{268900 - P_w}\right\} \times T_w\right]^{1/3} \tag{7}$$

$$q_{ewg} = 16.273 \times 10^{-3}\, h_{cwg}\,(P_w - P_g) \tag{8}$$

$$\eta_{th} = \frac{q_{ewg}}{I_r} \times 100 \tag{9}$$

Table 4 Design variable data used in the experimental and theoretical calculations.

Variable (Symbol)	Unit	Value
Average daily solar radiation (I)*	Watt-hr/m^2	~ 5320
Rate of incident solar energy on the horizontal surface of the passive solar still per unit area (I_r)**	W/m^2	~ 354.67
Water surface area (A)	m^2	0.01613

*The average solar radiation was determined from the average radiations for the months March-April in 2017 [39].

**Estimated from I_r = I/(15 hrs), since the study was conducted for 9 hours only.

6 Results and Discussions

As mentioned above, the designed solar still was quite small and was constructed to investigate the feasibility of having a household/industrial solar still for the purification of highly contaminated water and high freshwater throughput from the increase in cell performance. The maximum conventional efficiency that the designed solar still achieved was approximately 18.3%, from Eq. (1), with a production capacity of 5.5 mL/day, i.e. equivalent to 341 mL/day·m^2. However, a higher production capacity of 7.2 mL/day (446.4 mL/day·m^2) was achieved with a lower efficiency of 6% when the feedwater was four times higher (120 mL instead of 30 mL). The lower production rates are attributed to the low amounts of feedwater initially added to the system at 30 mL/day when compared to 120 mL/day (despite the fact that a higher performance was observed for a feed rate of 30 mL/day, freshwater production was lower than that at 120 mL/day). Table 5 shows the effect of different feed quantities, associated with water depth, on the still performance calculated with Eq. (1).

Comparing our results with previous works on single-basin solar stills, our daily production rates normalized to the water surface area (341~446 mL/day·m^2) were found to be lower by approximately one order of magnitude as compared to 4300 mL/day·m^2 [20], 3911 mL/day·m^2 [21], and 2595 mL/day·m^2 [22]. This sharp reduction in production rate is believed to be associated with the maximum basin volume, which was 322.6 cm^3 for our design, i.e. much smaller than in the previous design works (5040 cm^3 maximum volume) [22]. Even though we scaled down our system volume 15-fold compared to the literature, our mini-solar basin still had quite good production rates of ~446 mL/day·m^2. Thus, if one is capable of scaling up our system volume 15-fold while keeping the same design, the author believes that it will be possible to achieve a production rate of up to 5115~6690 mL/day·m^2, which is high enough to surpass most of the current literature results on single-basin solar stills. This could be possible because the polystyrene insulation and the blackened still walls/basin play a key role in improving the performance by keeping a high temperature, decreasing heat loss, and improving solar absorption.

The temperatures of the water and the glass were recorded and averaged for the different studied feed quantities. The observations turned out to be as expected, where the water temperature was always higher than the glass temperature; therefore, water condensated on the glass cover due to the convention that heat usually flows from a hot place (the water) to a cooler place (the glass cover). Another finding that matched the literature estimations was that the greater the difference between the water and the glass temperature, the higher the condensation rate obtained and the higher the efficiency. This is absolutely clear from Figure 5, in which the least temperature difference between the water and the glass (1.37 °C) was observed for the 120 mL/day sample (lowest efficiency), while the highest difference (2.14 °C) was observed for the 30 mL/day sample, which was the most efficient at 18.3% efficiency (or 20.54% efficiency according to Eq. (3) from the experimental calculations considering the depth factor). The maximum temperature difference in a single-slope still reported in the literature was about 5 °C [37,38].

Table 5 Solar still performance and daily production with respect to different feed quantities.

Feed (mL/day)*	Water Depth (mm)	Distillate (mL/day) [mL/day·m^2]	Efficiency (%)**
120	7.5	7.2 ; [446.4]	6
80	4.4	6.8 ; [421.6]	8.5
60	3.7	6.2 ; [384.4]	10.3
30	1.8	5.5 ; [341.0]	18.3

*Feed-side area: 12.7 × 12.7 cm (5’’ by 5’’) = 161.29 cm^2

**This experimental efficiency was calculated using Eq. (1)

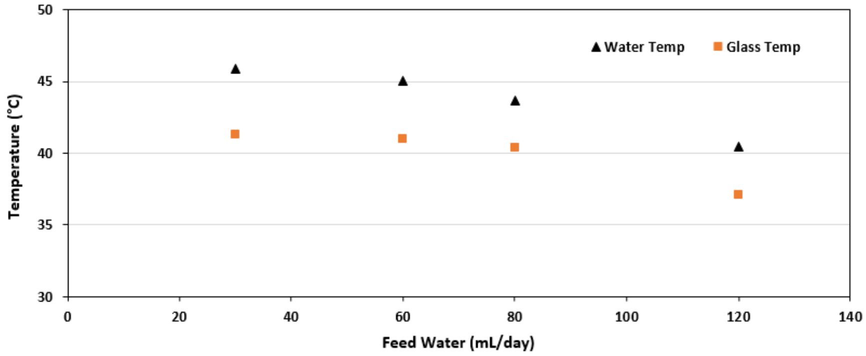

Figure 5 Effect of using different feedwater quantities on the average temperature difference.

A good estimation of the efficiency increase rate can be obtained from Figure 6 by applying the determined polynomial equation to the different experimental feed quantities. It was noted that an increase in feedwater will result in reducing the overall efficiency of the solar still. This data guided us in calculating the exact number of stages (or days) that were required to treat 50% of the feed, considering the feed to be in mL and not in mL/day for this task, for the different studied feed scenarios as shown in Table 5 and Figure 5. To check the feasibility of the designed solar still for water purification, feed values were considered to be constant volumes that were independent of time. The feed was injected into the system at once and not on a daily basis. This assumption may not seem logical, however, what we were looking for was to determine the number of days required to treat 50% of a constant feed volume of 30, 60, 80, and 120 mL. The results showed that a minimum of 3, 5, 6, and 9 days (or stages) was needed to treat 50% of the feed values 30, 60, 80, and 120 mL, respectively, as shown in Figure 7.

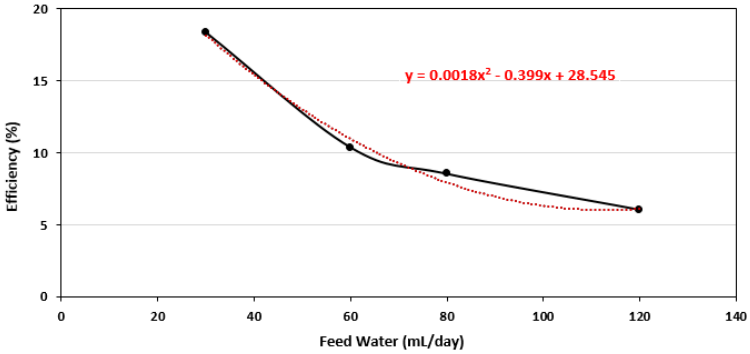

Figure 6 Effect of using different feedwater quantities on still efficiency.

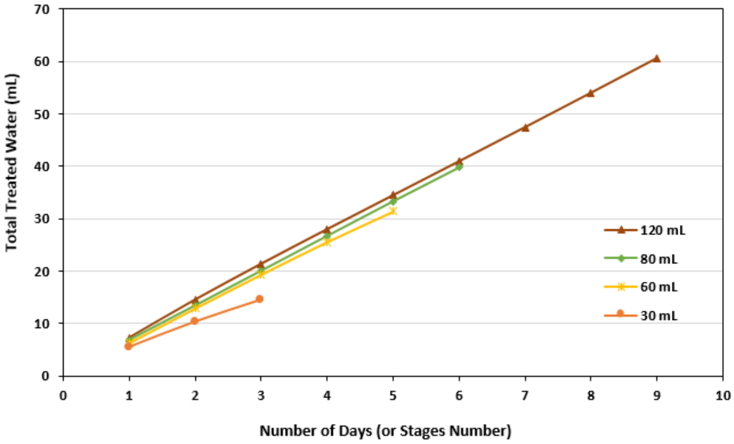

Figure 7 Estimated number of days (or stages) required to treat 50% of different feedwater quantities in mL.

Experimental and modeled efficiencies were calculated from the previously given equations, as reported in Figure 8. The experimental results were determined from Eqs. (1) and (3), while the theoretical model results were calculated from Eq. (9). The added and proposed correction factor of depth to Eq. (3) played a key role in optimizing the experimental results and giving a good approximation. It is worth mentioning that the optimized efficiency equation, Eq. (3), was only valid when the water depth was in the range (1 mm $\leq$ Hw $\leq$ 20 mm). There was a good agreement between the experimental and the theoretical results, which indicates that the theoretical model was capable of correctly estimating the performance of the solar still. The performance results demonstrated the effectiveness of the designed solar still for water distillation, with a maximum observed performance of 20.54% calculated from Eq. (3).

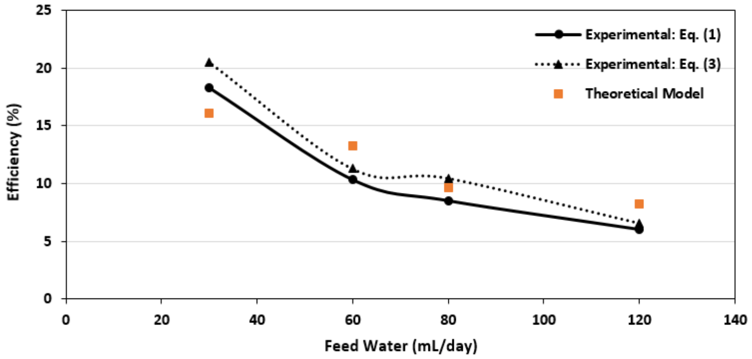

Figure 8 Experimental and theoretical modeled efficiencies for different feed quantities.

A comparison study between various designed passive solar stills with a single-slope configuration was conducted in this study, as shown in Table 6. Kalita, *et al.* [12] have reported that the maximum possible theoretical efficiency for a single-slope passive solar still would be 21.46% when solar insolation is 623.52 W/m^2. However, our findings predict that the performance should be between 6% and 20.54% (depending on the feed quantity) when solar insolation is about 354.67 W/m^2. The water quality was investigated by measuring the conductivity of both the feed and the distillate. The measured averaged conductivities for the feed and the distillate were about 1075 µS/cm and 32.3 µS/cm, respectively. In other words, the system showed > 97% treatment and/or removal efficiency of total dissolved solids (TDS). The water quality results showed that the system was effectively able to remove most of the impurities from the brackish water.

Table 6 Performance comparison of single-slope passive solar still with previous studies.

Comments	Efficiency (%)	Ref.
Dyes were utilized	17.2 ~ 26	[40]
Plastic still	≈ 16	[41]
Blackened surface and thermocol insulation	≈ 8.5	[42]
Theoretical efficiency with insolation of 623.52 W/m^2	< 21.46	[12]
Two solar stills with 23° and 30° inclination	17 ~ 20.5	[9]
Solar still before and after being coupled with a shallow solar pond, respectively	13 ~ 17	[19]
Glass still with polystyrene insulation and blackened walls and basin	6 ~ 20.54	This study (2017)

7 Conclusions

A designed and constructed solar still was utilized to check the feasibility of using solar distillation systems for achieving high freshwater throughput and/or still performance in personal/industrial applications. An AutoCAD preliminary design was used in the construction phase of the still, with an inner surface area of 12.7 cm × 12.7 cm and a maximum volume of 322.6 cm^3. Different feed samples were prepared for the experiment, which was conducted in Los Angeles from March to April 2017. A performance analysis of the still was performed by both experimental and theoretical calculations.

Comparisons showed that the theoretical model of the still was in good agreement with the experimental results. Therefore, it can be concluded that the theoretical model can be used for estimating the performance of single-slope passive solar stills. The formulated experimental equation was modified with a depth correction factor and was successfully able to identify the system efficiency in agreement with the theoretical analysis. The results also revealed that it was possible to achieve a performance efficiency of up to 20.54%, which corresponds to a production amount of 384.4 $mL/day{\cdot}m^2$ (6.2 mL/day) of freshwater. Meanwhile, lowering the feed quantity from 120 to 30 mL/day resulted in increasing the experimental performance efficiency from 6% to 18.3%, respectively, with lower production rates, decreasing from 446.4 to 341 $mL/day{\cdot}m^2$ (7.2 to 5.5 mL/day), respectively. Polystyrene insulation and blackened still walls/basin played a key role in improving the still's performance. The designed mini-basin solar still had quite good production rates of ~446 $mL/day{\cdot}m^2$ despite the fact that the system was 15-fold lower in volume than reported volumes in the literature for single-basin designs. If we scale up our system volume by 15-fold to be comparable to the basin size in the literature, we may be able to achieve a production rate of up to 5115~6690 $mL/day{\cdot}m^2$, which is high enough to surpass most of the water daily production rates reported in the literature.

The author suggests that there are other parameters that should be further studied and investigated in future studies, including (1) insulation material, (2) basin color, and (3) inclination angle. Solar stills are inexpensive systems, scalable and easy to fabricate for use in the production of distillate water. Hence, continuous efforts in the field of solar distillation and solar stills must be considered by the scientific community for further system evaluations to increase system performance and freshwater production to reach the maximum possible limits.

Nomenclature:

η: Solar still efficiency, %
D: Distillate flowrate, mL/day
F: Feed flowrate, mL/day
Q: Daily output, L
L: Latent heat of vaporization of water, J/kg
A: Area of the water surface in the solar still, m^2
I: Average daily solar radiation, MJ/m^2
H: Depth, mm
q: Rate of heat/energy transfer, W/m^2
h: Heat transfer coefficient, W/m^2K
T: Average temperature, K
P: Vapor pressure, N/m^2

Subscripts:

$e1$: Experimental: Eq. (1)
$e2$: Experimental: Eq. (3)
i: Internal instantaneous
m: Maximum
w: Water
g: Glass
cwg: Convective heat transfer from water to glass
ewg: Evaporative heat transfer from water to glass
th: Theoretical model: Eq. (9)
r: On the horizontal surface of the passive solar still

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