

Highly Efficient Solar Still based on Polystyrene

Hisham A. Maddah

Abstract—Solar still is a promising alternative to current desalination technologies owing to its inexpensive operation. Here, we investigate on polystyrene insulation used in single slope passive solar still to achieve high performance at different feed flowrates. Theoretical models and experiments are utilized to determine heat transfer coefficients and still efficiency. Results showed that decreasing feed flowrates increases the still efficiency due to the high water-glass temperature difference. A noticeable increase in the evaporative coefficient is also observed at low feed rates.

Index Terms— Heat transfer, Insulation, Solar Energy, Water Distillation

1. INTRODUCTION

World's drinking water demand is rapidly increasing in the last few decades due to the excessive amounts of produced contaminated water [1], [2]. Available Earth's fresh water sources accounts for only 1% and are limited to rivers, lakes and underground reservoirs [3], [4]. Currently, water distillation and membrane separation processes are utilized by governments and industries for seawater desalination in order to meet the high demand on fresh water [5]–[7].

Water distillation has been known since the ancient era where water is heated from any heating source and is then condensed on a tilted plate to produce fresh water. Current conventional distillation methods require high energy input and are very expensive for the production of freshwater [8]. Recent studies discovered the use of a promising and emerging technology for water distillation; this technology is called solar stills. The advantage of solar stills is that they utilize free, available, and environmentally friendly solar energy, to be employed for seawater desalination [9].

Solar stills can be classified into passive stills and active stills. The difference between the two categories is that passive still basin is heated directly and without the involvement of any active element like heaters or boilers, but active stills have active heating elements. In other words, passive stills have a simple design and no extra heating system is required [10].

The major problem with using solar stills is that a lot of heat is lost inside the still which results in having a low performance [11]. There are various design parameters and surrounding factors which play a key role in determining the overall still efficiency. Manipulations in certain parameters would increase the daily distillate production of solar stills. For instance, higher solar radiation and lower feed rate will certainly increase the still performance [12].

The objective of the present paper is to evaluate the still performance, for different feed rates, using polystyrene for insulating a designed small passive single slope solar still. The estimation of convective, evaporative and radiative heat

transfer coefficients is calculated for the different water feed scenarios. Theoretical and experimental calculations are employed to calculate the maximum possible efficiency.

I. Experimental Set-up

A small single slope passive solar still was designed for the experimental setup. Cheap materials including plexiglass sheets, silicon sealant, construction adhesive, black rubber pad, Aluminium foil, polystyrene foam sheets, black insulation duct tape, and a removable cover neutral putty were utilized for the construction of the still. Materials were carefully selected to ensure the best insulation and to keep the absorbed solar energy inside the still to raise water temperature more effectively. A slope angle of 20° was selected in the design of the removable solar still cover. The suggested solar still tank dimensions in this study were quite small (Table 1), and used to evaluate the impact of insulation on the heat transfer coefficients in the passive solar still.

Table 1. Assigned dimensions of the different glass parts utilized in the construction phase

Part Location	Quantity	Dimensions*
Top side (cover)**	1	12.7 x 17.78 cm (5'' by 7'')
Bottom side	1	12.7 x 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 x 2 cm (5'' by 0.78'')
Back side (high rise)	1	12.7 x 8.7 cm (5'' by 3.5'')
Partitions	2	12.7 x 2 cm (5'' by 0.78'')

*Glass thickness of 3 mm is not considered; **Sealant rubber is added to the glass cover to close any gaps; ***There is 1 cm bottom-distillate-side-gap filled with sealant; IR: Initial rise; AR: Angle rise.

The designed solar still container was then placed in an open area in the southern region of Los Angeles, CA (34°01'13.6"N, 118°17'45.1"W) during the Mar-April 2017, from 9:00 am to 6:00 pm for several days, to measure the effect of solar radiation on the temperature difference between water and glass on an hourly basis. High-temperature difference induces water evaporation and condensation rates and thereby enhancing the performance of the solar still to produce distillate water. Synthesized brackish water samples of 30, 60, 80 and 120 mL with an average conductivity of 1075 $\mu\text{S}/\text{cm}$ were used as the daily feed for the experiment work.

The designed passive solar still is shown in Figures 1 and 2. Figure 1 shows the constructed glass solar still without

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being insulated yet. However, Figure 2 illustrates the designed still after putting the polystyrene wall insulations with other materials used for the installation of the removable glass cover.

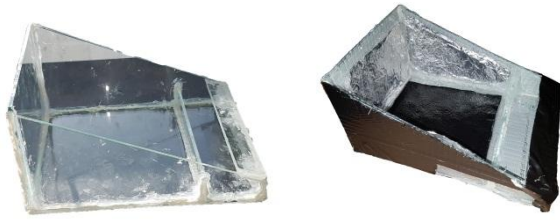


Fig.1

Fig 2

Figure 1. The initial construction of the glass passive solar still before being insulated

Figure 2. The final construction of the glass passive solar still after being insulated

II. MATHEMATICAL EQUATIONS AND DATA

Calculations of different solar still parameters are investigated and determined by using mathematical equations and models as reported in earlier works from using the general heat balance equation. Partial pressures of the water and the glass sides are determined from Eq. (1) and Eq. (2), respectively [13]–[15].

$$P_g = \exp \left[25.317 - \frac{5144}{T_g} \right] \quad (1)$$

$$P_w = \exp \left[25.317 - \frac{5144}{T_w} \right] \quad (2)$$

The estimation of the solar still efficiency and its heat transfer coefficients can be quantified from water-side and glass-side temperatures. Convective heat transfer coefficient from water to glass is estimated from Eq. (3) where the rate of heat transfer from water to glass is determined from Eq. (4). Evaporative heat transfer coefficient values from water to glass are calculated from the observed water and glass temperatures, partial pressures, convective coefficients, and from Eq. (5); using Table 2. The evaporative heat transfer coefficient is the most critical parameter since it indicates the still performance and the amount of distillate water [13]–[15].

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

$$q_{ewg} = 16.273 \times 10^{-3} h_{cwg} (P_w - P_g) \quad (4)$$

$$h_{ewg} = \frac{16.273 \times 10^{-3} \times h_{cwg} (P_w - P_g)}{T_w - T_g} \quad (5)$$

Radiative Heat transfer coefficient from water to glass is calculated from Eq. (6) and Eq. (7). Total heat transfer coefficient from water to glass is determined from Eq. (8).

$$h_{rwg} = \epsilon_{eff} \sigma (T_w^2 + T_g^2) \times (T_w + T_g) \quad (6)$$

$$\epsilon_{eff} = \frac{1}{\left[\frac{1}{\epsilon_g} + \frac{1}{\epsilon_w} - 1 \right]} \quad (7)$$

$$h_{wg} = h_{cwg} + h_{ewg} + h_{rwg} \quad (8)$$

The overall solar still efficiency is determined theoretically and experimentally from Eq. (9) and Eq. (10), respectively [13]–[15].

$$\eta_{exp} = \frac{D}{F} \times 100 \quad (9)$$

$$\eta_{th} = \frac{h_{ewg} (T_w - T_g)}{I_r} \times 100 \quad (10)$$

Table 2. Variable and parameter values assigned in the calculations of heat transfer coefficients

Variable/Parameter (Symbol)	Unit	Value
Feed flowrate (F)	mL/day	30, 60, 80 and 120
Average daily solar radiation (I)	Watt-hr/m ²	5320 [22]
Radiation time (t)	hr	9:00 to 18:00; or 9 hrs
Rate of incident solar energy (I _r)	W/m ²	354.67
Water surface area (A)	m ²	0.01613
Stefan Boltzmann constant (σ)	kg s ⁻³ K ⁻⁴	5.67 × 10 ⁻⁸ [23]
Glass emissivity (ε _g)	-	≈ 0.86 [20, 24]
Water emissivity (ε _w)	-	≈ 0.95 [20, 24]

III. RESULTS AND DISCUSSIONS

The heat transfer coefficients in the solar still are determined to be larger for lower feed rates. Evaporative, convective and radiative heat transfer coefficients from water to glass are estimated for the four feed scenarios of 30, 60, 80 and 120 mL/day in Figures 3, 4, 5 and 6, respectively. It is observed that the highest evaporative heat transfer coefficient is reserved for the 30 mL/day feed flowrate.

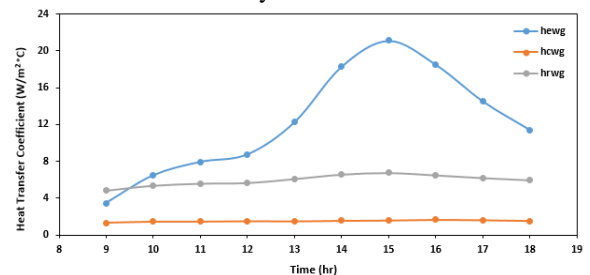


Figure 3. Solar still heat transfer coefficients with 30 mL/day feed flowrate

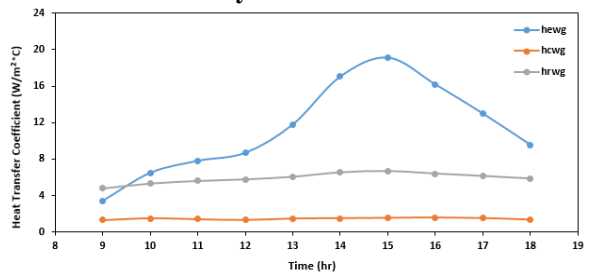


Figure 4. Solar still heat transfer coefficients with 60 mL/day feed flowrate

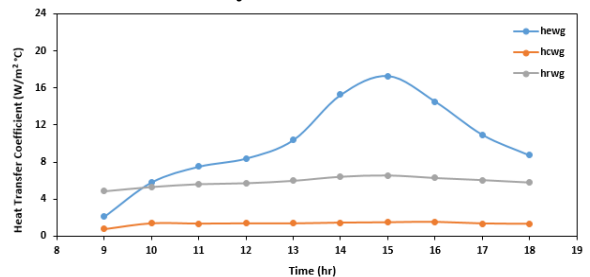


Figure 5. Solar still heat transfer coefficients with 80 mL/day feed flowrate

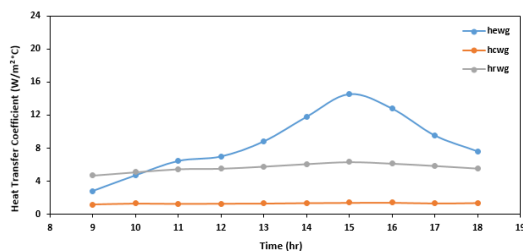


Figure 6. Solar still heat transfer coefficients with 120 mL/day feed flowrate

A comparison between the averaged heat transfer coefficients of the passive single slope solar still is shown in Figure 7. It is clear that with decreasing the daily water feed rate, slight increases occur to the convective and radiative coefficients and a noticeable increase in the evaporative heat transfer coefficient. Figure 8 shows that there is a good agreement between theoretical and experimental efficiency calculations. For most of the time, the theoretical efficiency is larger than the experimental efficiency; which is logical. However, for the feed scenario of 30 mL/day, it is observed that the maximum experimental efficiency is slightly greater than the maximum theoretical efficiency. The lowest feed scenario of 30 mL/day achieved maximum efficiency since it has the highest evaporative heat transfer coefficient.

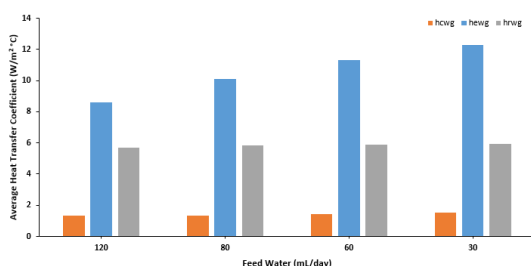


Figure 7. Average heat transfer coefficients for the different feed water flowrates

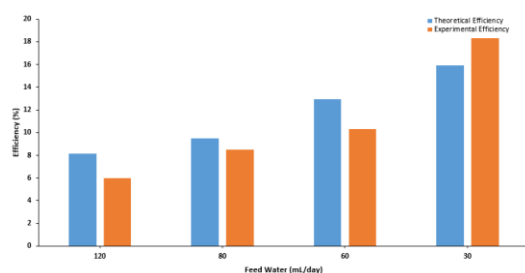


Figure 8. Solar still efficiencies for the different feed water flowrates

CONCLUSION

A small single slope passive solar still is designed from inexpensive insulating materials such as polystyrene and duct tapes. This study evaluates the still performance based on using polystyrene while having different feed flowrates. Different brackish water samples are prepared and the experiment work is conducted in Los Angeles during Mar-April 2017. Mathematical models and experimental calculations are utilized to determine convective, evaporative and radiative heat transfer coefficients and to calculate the maximum achievable efficiency. Results showed that decreasing feed flowrates improves the still performance

owing to the high-temperature difference between water and glass. Also, slight increases are observed in the convective and radiative coefficients with a much noticeable increase in the evaporative heat transfer coefficient. We have identified a good agreement between theoretical and experimental efficiency calculations. The lowest feed scenario of 30 mL/day achieved maximum efficiency since it has the highest evaporative heat transfer coefficient.

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