Thermal and Exergetic Analysis of a Solar Still

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Abstract. In this work an energy and exergy analysis of solar distillation process is presented. The analysis is based on the experimental observation of the simple basin type solar stills for 4 different initial volumes (5.5, 6.5, 7.5 and 8.5 L). Energy and exergy balance equations have been written for all components of the solar still including glass cover, brine and absorber plate. The thermodynamic models for the energy and exergy analysis are presented on the critical heat transfer correlations in literatures for the simple basin type solar still. The results show that maximum values are reached in the energy efficiency of 45.6, 41.5, 35.7 and 31.8%, however exergetic efficiency for maximum values are 7.5, 7.2, 7 and 5.4%, corresponding to volumes 5.5, 6.5, 7.5 and 8.5 L respectively.

1. Introduction
The availability of drinking water is reducing day by day; where as the requirement of drinking water is increasing rapidly. To overcome this problem there is a need for some sustainable source for the water distillation (purification). Solar still is a useful device that can be used for the distilling of brackish water for drinking purposes. The energy and exergy performance of solar stills has been investigated by many researchers. Mehdizadeh [1], used energy and exergy calculations to determine the optimum operating conditions for a solar still that uses the benefits of both reverse osmosis and nano-filtration technologies. They showed promising results for the use of the integrated reverse osmosis and nano-filtration process. Dehghan et al [2], showed a study for thermodynamic modeling of a novel portable solar still through the first and second laws analysis, where the daily average energy and exergy efficiencies of the solar still are 19.8% and 0.95%, respectively, also they found that the rate of exergy destructions in solar still components is proportional to the incident solar intensity. The largest exergy destruction in concentrated in the thermoelectric module, with a value of 63.4% of the total exergy destruction, while the glass cover has the smallest value share with 0.8%. On the other hand, Basel [3], designed and build a simple transportable hemispherical solar still and evaluated its performance experimentally under outdoors of Dhahram climatic conditions. In his experiments found that the solar still from 2.8 to 5.71 L/m² day and with an average efficiency of 33%.

Torchia et al. [4], they made a theoretical exergy analysis on stationary and transient state of a solar still, focused on the study of the destruction of exergy in the distellers’ components, such as, plate collector, brine and glass cover. They solve energy balances to find the temperatures of each component and turn these temperatures are used to calculate the energy and exergy flows. The results show that the exergetic efficiency it is: 12.9%, 6% and 5%, for the collector, brine and solar still respectively. Ranjan [5], show thermodynamic models for the energy and exergy analysis in a simple basin type solar still. The exergetic efficiencies are estimated to be between 19% and 26% for a triple effect system, 17–20% for a double effect system, and less than 5% for a single effect system. Productivity increases significantly by the use of integrated solar stills with better efficiency.

The overall energy and exergy efficiency of the integrated systems rises up to 62% and 8.5%, respectively, using single effect solar stills. Energy efficiency and productivity of the conventional
solar stills is found to below in the range of 20-46% and less than 6 L/m²/day, respectively, for most cases, even under optimized operating conditions. In this work, a study for first and second law applied to the distillation process using a solar still is shown. The results obtained can be used to evaluate the process and indicate what is the real energy quantity used in the distillation process of brine.

2. Experimental procedure
The solar still employed is a closed container with a transparent glass cover which has a tilt angle of 40°, which allows the passage of the solar radiation. Inside the zone of the solar still it’s found an absorber plate painted in matte black, is where the fluid is deposited to distill (brine), with an area of 0.36 m², at the same time there are 4 gutters connected to the absorber plate to collect the condensate. In the solar still 4 experimental tests were performed, using an initial volume of brine different, for each test data from temperature and the solar radiation incident on the device were obtained. The instrumentation used for obtaining temperatures, was a Compact FieldPoint equipment, type K thermocouples and a Pyranometer Eppley model 8-48, they are obtained recording data every 10 minutes during an interval of time from 10:00 am to 18:00 pm, since in this period of time there is more insolation. In figure 1 the solar still is shown.

![Solar Still and instrumentation equipment](image)

**Figure 1.** Solar Still and instrumentation equipment

3. Energy balance equations
The energy balance is analysed from different parts of the system such as: (a) Glass Cover, (b) Fluid and (c) Absorber plate, for which a set of equations that depend only on the temperature are obtained.

The total energy received by the glass cover is equal to the incident solar radiation and evaporative, convective and radiative heat transfer from the brine minus the sum of the energy loss between the glass cover and the sky by radiative and convective heat transfers and the energy accumulation within the glass cover. The equation for the glass cover is given by:

$$Q_{g} = (\alpha_{g} I(t)A_{g} + Q_{r, g} + Q_{w, g} + Q_{c, g}) - (Q_{r, g} + Q_{w, g} + (m_{g} C_{p, g})dT_{g}/dt))$$  \( (1) \)
The total energy received by the brine in the solar still is equal to the incident solar radiation and convective heat transfer between absorber plate and water minus the sum of the energy from the water to the glass cover by radiation, convection and evaporation and the energy accumulation within the brine. The equation for the brine is given by:

\[ Q_{b,s} = (\alpha_w I(t) A_r + Q_{c,p,w}) - (Q_{r,w} + Q_{c,w} + Q_{ev} + (m_w C_{pw}) \frac{dT_w}{dt}) \]

The total energy received by the absorber plate is equal to the incident solar radiation minus the exergy losses to the environment and the energy accumulation within the absorber plate. The equation for this case is given by:

\[ Q_{a,p} = (\alpha A_r) - (Q_{c,p,a} + Q_{g} + Q_{ev} + (m_C p_C) \frac{dT_a}{dt}) \]

The solar still overall thermal efficiency is considered to be the ratio of evaporative heat transfer to the solar irradiance on the absorber plate and it is given by the following equation.

\[ \eta_t = \frac{h_{cr,cr} A_r (T_a - T_g)}{I(t) A_r} = \frac{Q_{ev}}{I(t) A_r} \]

4. Exergy balance equations

The exergy balance equations for the different parts of the system are given here.

The total exergy of the glass cover is received by the sun and brine minus the exergy from the glass cover to environment, exergy destruction of the glass cover and the accumulated exergy within the glass cover. The equation for the glass cover is given by:

\[ Ex_{g,s} = \alpha_g Ex_{sun} + Ex_{g,a} - Ex_{g} - dEx_g / dt \]

The total exergy of the brine is received by the sun and absorber plate minus the evaporation exergy from the brine to the glass cover, exergy destruction of the brine and the accumulated exergy within the brine. The equation for the brine is given by:

\[ Ex_{b,w} = \alpha_w \tau_x Ex_{sun} + Ex_{b,p} - Ex_{b} - dEx_b / dt \]

The total exergy of the absorber plate is received by the sun minus the exergy destruction of the absorber plate, exergy transfer from absorber plate to the brine, exergy from the absorber plate to the environment and the accumulated exergy within the absorber plate. The equation for the absorber plate is given by:

\[ Ex_{a,p} = \alpha_p \tau_x \tau_p Ex_{sun} - Ex_{a,p} - dEx_a / dt \]

Hence, the expression for the overall exergy efficiency of the solar still can be defined as the ratio of the rate of useful exergy output of solar still to the rate of total input exergy. The rate of useful exergy output of the solar still is the total rate of useful exergy associated with the useful evaporation heat transfer rate.

\[ \eta_{ui} = \frac{h_{cr,cr} A_r (T_a - T_g)}{A_r I(t)} \times \left[ 1 - \frac{T_a + 273}{T_a + 273} \right] \]

\[ = \frac{1 - T_a + 273}{T_a + 273} \times \left[ 1 + \frac{1}{3} \frac{T_a + 273}{6000} \right] - \frac{4}{3} \left( \frac{T_a + 273}{6000} \right) \]
4. Results
With the experimental data that they have for each of the tests and making use of the equations that have previously been mentioned, it is possible to obtain the curve of energy efficiency and exergetic efficiency. The results for efficiency corresponding to each test are shown in figure 2 to 5.

![Figure 2. Variation of energetic and exergetic efficiency and solar radiation for 5.5 L of brine](image)

![Figure 3. Variation of energetic and exergetic efficiency and solar radiation for 6.5 L of brine](image)
5. Discussion
The solar still show a maximum energy efficiency of 45.6% for 5.5 L of brine; however, for 8.5 L of brine only an efficiency of 31.8 % was reached. In figures 2 to 5, is showed an increase in efficiency, reaching the highest values at the end of the test, this is because that the energy is stored in the device as time passed. It was also found that the average energy efficiency of the solar still decreased by 13.8% when the saline water depth increased by 39%.
The variations that are showing efficiency is due to weather conditions, since the solar radiation is changing because that is not constant and varies its intensity due to cloudiness, dust, pollution, etc., due to these changes the heat transfer by evaporation is affected and therefore the thermal efficiency of the device. Therefore the device on average only used the 38.7% of the energy proceeding from the sun. According to the analysis and the results obtained, the exergy efficiency is much smaller compared with the energy results, reaching maximum values in the exergetic efficiency of 7.5, 7.2, 7 and 5.4%, corresponding to volumes 5.5, 6.5, 7.5 and 8.5 L respectively. However, it is observed that there is a difference of 0.2 %, for exergy efficiency when the device is operated with 5.5, 6.5, and 7.5 L, so for these cases, the depth of brine to be distilled is not relevant compared with the test performed with 8.5 L of brine. It is seen that the exergy efficiency is much lower than the energy efficiency.
According to the study carried, the device efficiency is influenced by the brine depth showing that in volumes over 7.5 L, a bigger energy supply is required, thus the process becomes slower and in consequence the energetic and exergetic efficiency decreases. As a result, wide areas with small thickness are indicatives of a better evaporation and therefore a better efficiency.

6. Conclusion

The values of exergetic efficiency (second law of thermodynamics) in solar stills are quite low compared to energy efficiency (first law of thermodynamics). The efficiency of the solar still is increased if the temperature value is higher in the fluid, so the heat fluxes that take advantage are higher and, therefore, the efficiencies increase. The energy efficiency and exergetic, have different behaviors and this depends on the climatic conditions of operation, i.e., if the energy and exergy analysis are compared, the latter is better since it gives a real insight into the working of the device to carry out the distillation process. So the exergy analysis for the solar still represents the quality of the energy that is contained in this. That indicates how much of the energy coming from the Sun is taken advantage in the system.

7. Appendices

Nomenclature

| Symbol | Description |
|--------|-------------|
| $A$    | Area, m$^2$ |
| $C_p$  | Specific heat, J/kg K |
| $Ex$   | Exergy, W/m$^2$ |
| $h$    | Heat Transfer coefficient, W/m$^2$ K |
| $I(t)$ | Solar Radiation, W/m$^2$ |
| $Q$    | Heat Transfer, W |
| $T$    | Temperature, ºC |

Greek letters

- $\alpha$: Absorptivity
- $\tau$: Transmissivity
- $\eta$: Efficiency

Subscript

- $c$: Convection
- $ev$: Evaporation
- $g$: Glass
- $p$: Absorber plate
- $r$: Radiation
- $sun$: Sun
- $t$: Total
- $w$: Water
- $\infty$: Environment

8. References

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