Irreversibility analysis in the process of solar distillation

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Abstract. In this work an irreversibility analysis for the thermal process of solar distillation of three different substances is presented, for which it employs a solar still of a slope where three experimental tests with 5.5 L of brine, river water and MgCl₂ were performed. Temperature data principally in the glass cover, absorber plate, fluid, environment and the incident solar radiation on the device were obtained. With measurements of temperature, solar radiation and exergetic balance, irreversibilities are found on the device. The results show that the highest values of irreversibilities are concentrated in the absorber plate with an average of 321 W, 342 W and 276 W, followed by the cover glass with an average of 75.8 W, 80.4 W and 86.7 W and finally the fluid with 15.3 W, 15.9 W and 16 W, for 5.5 L of brine, river water and MgCl₂.

1. Introduction

In the industrial processes, the distillation has an infinite number of applications, from petrochemical industry to the pharmacist, however to realize the stills separation electrical are used, which consume a large amount of conventional energy or condensing the steam water that comes from the boilers, and to turn these consume hydrocarbons from the oil, this process is very expensive and it pollutes the atmosphere so the use of the renewable energy sources is an alternative to the distillation process by means of the application of the solar energy. This way the solar distillation has turned into a wide expansion, thanks to the fact that by means of the solar stills, it is possible to obtain drinking water.

The design of a solar device implies the evaluation of all the parameter that have on them, the irreversibility is important to evaluate the performance of the solar stills. In the search of the solar still topic literature several authors have worked on the exergy and irreversibility as applied to solar devices. Some results are shown in what follows.

Torchia et al. [1], they conducted a study of exergy in the stationary and transient state of a solar still, focused on the study of the destruction of exergy in the distillers 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 in the steady state the irreversibilities produced in the collector are 615 W/m² for a 935 W/m² solar energy input, whereas irreversibilities rates in the brine and in the glass cover can be neglected. On the other hand they found that the exergetic efficiency is: 12.9%, 6% and 5%, for the collector, brine and solar still respectively. 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, Ranjan [3], shows thermodynamic models for the energy and exergy analysis in a simple basin type solar still based on the fundamental heat transfer for a triple effect system, double effect system and a single effect system for the solar still. The results show that the energy efficiency
and productivity of the solar still are 20-46% and 6 L/m² day, respectively for all cases, for the exergetic efficiencies are estimated to be between 19% and 26% for a triple effect system, for a double effect system are between 17–20%, and less than 5% for a single effect system. He also found that the 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. In addition, it has also been made works on economic and thermo-economic analysis of solar stills, where the cost of desalination through solar stills is reported in the range of US $0.014 to 0.237/L, therefore it decreases further with the increase in efficiency. Kaushik et al [4] develop a thermodynamic model to estimate the overall exergy efficiency of the single effect horizontal basin type ideal passive solar stills. The solar still was evaluated in June with water depth of 0.04 m and found that the results of energy efficiency were from 8 to 87.2% and the daily energy and exergy efficiency of the solar still is 20.7 and 1.31%, respectively. It is also confirmed that the overall exergy efficiency increases with the increase of water temperature and decreases with the increase of ambient temperature. Basel [5], designed and built 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%. Kumar and Tiwari [6], presented an expression for instantaneous exergy efficiency of a passive solar still, considering the effect of the design, climatic parameters, effective absorptivity of basin liner, glass cover tilt and wind velocity. The results showed that with a decrease in absorptivity with time is from 0.9–0.6, the energetic and exergetic efficiencies decrease by 21.8% and 36.7% respectively, also with the effect of the glass cover tilt the efficiencies decreased by 0.75% and 0.47% per degree increased in tilt and these efficiencies increased rapidly up to a wind velocity of 2 m/s.

In this work the irreversibility analysis in a solar still are shown, these are obtained when the operation of a solar still with 5.5 L of brine, river water and MgCl₂ is evaluated.

2. Experimental procedure

The solar distillation process is: the solar still is partially filled with some fluid (brine, river water and MgCl₂) in an absorber plate which is a black surface used to absorb incoming radiation after it passes through the glass cover and the fluid, the absorber plate increases its temperature and transfers heat to the fluid, after this, water evaporates at the free surface. A natural convection flow of humid air circulating inside the enclosure takes place due to the temperature difference between the free surface of the heated fluid and the upper cool cover, and this inclined glass cover serves as a condensing plate where the distillate water runs by gravity along its internal face to a small collector gutter. The solar still employed has a tilt angle of 40°, with an area of 0.36 m² for the absorber plate. The solar still considered as reference in this work is shown in figure 1.

![Solar Still](image)

**Figure 1. Solar Still**

The instrumentation used for obtaining temperatures when the solar still is evaluated with 5.5 L of brine, river water and MgCl₂, is with an equipment Compact FieldPoint, type K thermocouples and a Pyranometer Eppley model 8-48, they are obtained recording data every 15 minutes during an interval of time from 10:00 am to 18:00 pm, since in this period of time there are more insolation.
3. Irreversibility for the solar still
One of the important uses of the second law of thermodynamics in engineering is to determine the best theoretical performance of systems. By comparing actual performance with the best theoretical performance, insights often can be gained into the potential for improvement. A process is called irreversible if the system and all parts of its surroundings cannot be exactly restored to their respective initial states after the process has occurred.

The irreversibility 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 and can be calculated according to reference [1, 2, and 3]. The exergy accumulation in the glass cover, fluid and absorber plate is assumed to be negligible.

The irreversibility balance in the glass cover is evaluated considering the exergy flow through glass cover as shown in figure 2 and equation (1).

\[
I_g = Ex_{g-sun} + Ex_{d-g} = \alpha_g Ex_{sun} + Ex_{w-g}
\]

Where \(\alpha_g\) is the amount of the solar exergy absorbed by glass cover, \(Ex_{w-g}\), is the sum of exergy associated with the heat exchanges between the water surface and the glass cover, and \(Ex_{g-s}\), represents the exergy losses from the glass cover to the environment by the heat exchange processes of radiation and convection.

The irreversibility balance in the fluid (brine, river water and MgCl\(_2\)), is evaluated considering the exergy flow through the fluid as shown in figure 3 and equation (2).

\[
I_w = Ex_{d-w} = \alpha_w \tau \cdot Ex_{sun} + Ex_{p-w} - Ex_{w-g}
\]

Where, \(\alpha_w\) is the part of the incident solar exergy absorbed by water and useful exergy from the absorber plate \(Ex_{p-w}\), a fraction of it is used as the exergy involved during heat transfers between the water surface and glass cover inside the solar still \(Ex_{w-g}\) and remaining is destroyed \(Ex_{d-w}\).

The irreversibility balance in the absorber plate is evaluated considering the exergy flow through the absorber plate as shown in figure 4 and equation (3).
Figure 4. Exergy flow of the absorber plate

\[ I_p = Ex_{p-sun} + Exd_p = \alpha \tau g \tau w Ex_{sun} - Ex_{p-\infty} \]  

The absorber plate of the solar still absorbs the solar exergy quantity \( \alpha \tau g Ex_{sun} \). This amount is shared between the brackish water heated by \( Ex_{p-w} \), and the exergy losses from the absorber plate to the environment \( Ex_{p-\infty} \).

4. Results

The temperatures obtained by the experimentation are shown in figure 5 to 7.

![Figure 5. Temperature variation of the solar still for 5.5 L of brine](image5.png)

![Figure 6. Temperature variation of the solar still for 5.5 L of river water](image6.png)

![Figure 7. Temperature variation of the solar still for 5.5 L of MgCl\(_2\)](image7.png)

Equations (1) to (3) are applied to the data obtained experimentally and the irreversibility is determined for each of the tests. In figures 8 to 10 are shown.
5. Discussion

For the process of solar distillation with different substances, it is possible to obtain results of temperature and radiation. In figures 5 to 7, the distribution of temperature and radiation with respect to time is shown, where the behavior in the temperatures measured are: \( T_w < T_g < T_p \), reaching maximum values in the fluid of 61.8 °C, 63.3 °C and 70.4 °C to 5.5 L of brine, river water and MgCl\(_2\), respectively. The test with MgCl\(_2\) acquires the highest temperature values, and this is due to the capacity of each one of the substances has to store the heat. According to these results, it is observed that it is not necessary that the solution to distill reach its boiling point to achieve condensation. In the solar radiation values were obtained in the range of 400-1129 W/m\(^2\), undergoing changes with time and therefore temperatures are affected.

Irreversibility variation for different parts of the solar still, such as: glass cover, fluid and absorber plate is shown in figures 8 to 10. As it can be seen, the irreversibility more important is found in the plate absorber, later he follows the glass cover and finally the fluid, such behavior is the same for the 3 tests performed. On the plate absorber, is reached the highest values in a range of 350 to 450 W in a time of 12:30 to 15:30 pm, in all three cases, however for the glass cover only reach values maximum of 100 to 146 W, for the fluid is concentrated irreversibility with smaller values with only 20.6 W, this being the maximum for all tests.
6. Conclusion
In this work, a study of irreversibility applied to process of solar still was done. In general for the solar distillation process using 3 different substances, the average irreversibility for absorber plate, glass cover, and fluid is 314.3 W, 80.96 W and 15.73 W respectively, and the total irreversibility of the whole system is 410.99 W. Therefore, 76.47% of the total irreversibility is related to the absorber plate which shows that the selection of an appropriate absorber plate has a great impact on the solar still performance. The reason behind the higher irreversibility of the absorber plate could be the temperature difference between the absorber plate and the sun and also the exergy dissipation from the absorber plate to the surrounding. Therefore, the selection of an appropriate absorber plate plays an important role in construction of solar stills. In addition, this work allows viewing how the concepts of the thermodynamics can be applied in the heating water process when solar cookers are used. Finally, the results obtained in this work can be useful in the taking of decisions for new designs of solar cookers.

7. Appendices

Nomenclature

| Symbol | Definition                  |
|--------|----------------------------|
| Ex     | Exergy, W                  |
| I      | Irreversibility, W         |

Greek letters

| Symbol | Definition                  |
|--------|----------------------------|
| α      | Absorptivity                |
| τ      | Transmissivity              |

Subscript

| Symbol | Definition                  |
|--------|----------------------------|
| g      | Glass                      |
| p      | Absorber plate              |
| sun    | Sun                        |
| w      | Water                      |
| ∞      | Environment                 |

8. References

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