Energetic, Exergetic and Entropy Evaluation in the Solar Distillation

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Abstract. This work shows the evaluation of energy, exergy and entropy for the process of solar distillation of river water. The solar still is of the slope with fins and is tested for 3 initial volumes: 2, 4 and 6 L, for which data of temperature and solar radiation are recorded. Subsequently, the Dunkle’s thermal model is applied and the energy, exergy and entropy balance are established to determine the efficiencies. The results show that the maximum energy efficiency in the solar still for 2, 4 and 6 L is 45%, 36% and 30% respectively, in exergy efficiency its maximum values are 4.7%, 3.8% and 2.9% for 2, 4 and 6 L of river water and finally the analysis of the entropy change, reached the maximum value of 1 kJ/Kg K in the 3 experimental tests.

1. Introduction

The distillation of water and binary mixtures through the use of renewable sources of energy, such as solar energy, is an issue increasingly studied and applied in many countries. Experiences from all over the world testify to the great importance and usefulness of this method of distillation, in addition to its ease of use. Without a doubt, it is more than evident the need to deploy new technologies that allow the utilization of the available energy, as it is in this case the solar radiation. The equipment used for this type of process are the solar still, to which studies on energy exergy and entropy balances have been carried out to observe the thermal behaviour of these devices, through a system of equations has been able to know temperature values in the cover glass, the water to be distilled and the absorber plate, as well as the volume of distilled water can be determined. Some works below are shown.

Khanmohammadi et al. [1] presented an experimental work on a comparative study of a solar still with internal reflector and phase change material composed of black gravel for thermal storage. The solar performance of still water, using the black gravel phase change composite material is 3.27 L/m² with an increase of 37.55%, instead of just using phase change material, with an improvement in energy and exergy efficiency of approximately 38% and 3.7% respectively. Suresh et al. [2] studied the thermal performance of a simple solar still whose five sides are exposed to ambient temperature and the supplies also allow connecting the glasses to increase the intensity of solar radiation. The energy efficiency is 45%.

On the other hand, Yousef et al. [3] showed an investigation of exergetic performance in a passive solar still, applied energy and exergy methodologies for all the components of the solar still
comprising the glass cover, water and the glass thickness. The results showed that the maximum energy and exergy efficiencies of the proposed system are 32.5% and 2.23%, respectively. Sarhaddi et al. [4] carried out a comparative study of the energy and exergy performance of two solar stills type cascade with and without phase change material storage (PCM), on sunny and semi-cloudy days. The maximum value of the energy and exergy efficiencies of the PCM-free solar still for a sunny day is 76.69% and 6.53%, respectively. Meanwhile, the maximum energy and exergy efficiencies of the PCM solar still for a semi-cloudy day sample are 74.35% and 8.59%, respectively. Agrawal et al. [5] used a house solar still, carried out an energy and exergia analysis to evaluate the performance of the device and found that the energy efficiency is always higher than the exergetic efficiency of the system. The values of daily energy and exergy efficiencies are 41.99% and 3.01% respectively. Saman et al. [6] they used a numerical approach based on a SIMPLE algorithm for the dynamic simulation of entropy generation, they analysed the effects of the proportion and temperatures of the glass cover and water in different types of entropy generations such as friction, diffusivity and thermal. The results obtained indicated that there is an increase in the different types of entropy generation with an increase in glass and water temperatures. For example, there was a 30% increase in diffusive entropy generation when the aspect ratio value changed from 2.58 to 5.3 for $T_g=30^\circ C$ and $T_w=40^\circ C$.

2. Experimental procedure

In this work, a solar still is used, inside there is an absorber plate with a finned honeycomb surface made of aluminium and painted in matt black with an area of 0.23 m$^2$, and the glass cover has an angle of 30°. In the solar still, 3 experimental tests were carried out, with an initial volume of: 2, 4 and 6 L of river water, for each test temperature data were obtained using type K thermocouples and incident solar radiation with an Eppley model 8-48 Pyranometer, the instrumentation used was through ADAM modules, which added to an interface in LabVIEW, can record temperatures and solar radiation every 10 minutes over a time interval of 10:00 am to 18:00 hrs. To carry out the experimentation, a solar simulator was used, which has the following characteristics: 6 halogen/quartz lamps of 500 W, 120 V, in addition to the simulator having an ignition and control device where the intensity of the lamps can be varied, this in order to simulate solar radiation in the solar still. The complete arrangement of the experimental tests is shown in Figure 1. Together, a cooling system was proposed to the solar still using a fan, this, in order to help the condensation process of the glass cover.

![Solar Simulator and instrumentation equipment](image)
3. Energy, exergy and entropy balance

To be able to perform an analysis of the performance of solar still, it is very important and essential to know the value of the heat transfer coefficients that occur inside the device, for this analysis, the thermal model of Dunkle’s. [7] who proposes a model to evaluate the heat transfer coefficients by convection and evaporation and they are given by:

\[ h_{c, w-g} = 0.884[\Delta T]^\frac{1}{3} \]  

\[ h_{v, w-g} = 0.0163h_{c, w-g} \frac{P_w - P_{gw}}{T_w - T_g} \]  

where

\[ \Delta T' = [T_w - T_g + \frac{(P_w - P_g(T_w + 273))}{268.9 \times 10^3 - P_w}] \]  

Moreover, 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.

**Glass Cover:**

Rate of energy absorbed from solar radiation + Rate of energy received from water mass by convection; evaporation and radiation = Rate of energy lost to the glass outer surface by conduction. The equation for the glass cover is given by:

\[ \alpha_g I(t) + q_{c, w-g} + q_{v, w-g} + q_{r, w-g} = q_{c, g-\infty} \]  

**Fluid**

Rate of energy absorbed from incident solar radiation + Rate of energy received from basin liner by convection = Rate of energy stored + Rate of energy lost to the glass inner surface by convection, evaporation and radiation. The equation for the brine is given by:

\[ \alpha_w I(t) + Q_{c, p-w} = m_wC_{p,w} \frac{dT_w}{dt} + q_{c, w-g} + q_{v, w-g} + q_{r, w-g} \]  

**Absorber Plate**

Rate of energy absorbed from solar radiation = Rate of energy lost to water mass by convection + Rate of energy lost to the ambient by conduction and convection+ Rate of energy stored. The equation for this case is given by:

\[ \alpha_w I(t) = Q_{c, p-w} + Q_{loss, p-\infty} + m_pC_{p,p} \frac{dT_w}{dt} \]  

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.

\[ \eta_I = \frac{h_{v, w-g}A_w(T_w - T_g)}{I(t)A_p} = \frac{Q_{v, w-g}}{I(t)A_p} \]  

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:
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:

\[
I_g = Ex_{e-w} + Ex_{d_s} = \alpha_s Ex_{sun} + Ex_{w-g} - \frac{dEx_g}{dt}
\]  
(8)

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:

\[
I_w = \alpha_w \tau_g Ex_{sun} + Ex_{p-w} - Ex_{w-g} - \frac{dEx_g}{dt}
\]  
(9)

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.

Exergy efficiency of solar stills is defined as the ratio of desired output exergy to the input exergy.

\[
\eta_{II} = \frac{A_p}{A_g} \eta_I = \frac{1}{\frac{T_w + 273}{1 + \frac{T_a + 273}{6000} - \frac{3}{4} A_p}}
\]  
(11)

The entropy of a system is associated with the presence of irreversibility. The entropy generation takes place in a system due to the irreversible nature of heat transfer and viscosity effects, within the fluid and at the solid boundaries.

The change in entropy during the variation of temperature is given by:

\[
\Delta s = \frac{\int_{T_1}^{T_2} dQ}{T} = m \int_{T_1}^{T_2} \frac{dT}{T}
\]  
(12)

The entropy analysis is carried out under the following considerations: the system is considered closed and the states defined for each instant evaluated are assumed in a stable state.

Hence the geometric mass and volume are constant, with this, the specific volume is constant and with the variation of the temperature each state can be determined. Thus, the entropy is determined only for the water since it is the one found in the liquid-vapour mixing zone. In this way, the entropy change will be the descriptor of the process when it is determined using the following equation:

\[
\Delta s = s_f + xs_{fg}
\]  
(13)

For the case of the change of entropy for the glass cover, absorber plate and fins, it was not carried out because there are no thermodynamic tables for the components.
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, exergetic efficiency and change entropy.

The results for efficiency corresponding to each test are shown in figure 2 to 4.
5. Discussion
The solar still show a maximum energy efficiency of 45%, 36% and 30% for 2 L, 4 L and 6 L of river water respectively, in figure 2, the variation of energy efficiency is shown where it is observed that as time passes, efficiency increases, reaching its maximum values between 15:40 hours and 16:30 hours, after this time the efficiency begins to decrease until the experimental tests are completed. Therefore the device on average only used the 37% of the energy proceeding from the sun.

According to the analysis and the results obtained, the exergy efficiency shown in figure 3 is much smaller compared with the energy results, reaching maximum values in the exergetic efficiency of 4.7, 3.8 and 2.9%, corresponding to volumes 2, 4 and 6 L respectively at approximately 16:00 hrs. However, it is observed that there is a difference of 1 %, for exergy efficiency when the device is operated with 2, 4 and 6 L, so for these cases, the depth of river water to be distilled is not relevant for the tree test, hence, exergy efficiency is much lower than energy efficiency.

The variations that efficiency are showing in the figure 2 and 3, 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. According to the study carried, the device efficiency is influenced by the brine depth showing that in volumes over 6 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.

In the entropy analysis of river water, as seen in figure 4, there is a concave downward parabolic behavior during the period of 10 a.m. at 6 p.m., noting that entropy increases what characterizes the heating process as an irreversible process, which is linked to energy losses and in this case they can be associated with steam leaks. The recorded results show that the maximum entropy is 1kJ/kg K in the 3 tests, at approximately 14:40 hours, and then the entropy begins to decrease during the process.

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 behavior’s 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. The evaluation of entropy is particularly useful since its concept through the values obtained for the fluid, allows us to know of the existence of the use of energy

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Nomenclature

| Symbol | Description |
|--------|-------------|
| $P$    | Pressure, Pa |
| $C_p$  | Specific Heat, J/kg K |
| $E_x$  | Exergy, W/m² |
| $h$    | Heat Transfer Coefficient, W/m² K |
| $I(t)$ | Solar Radiation, W/m² |
| $q$    | Heat Transfer, W |
| $T$    | Temperature, °C |
| $A$    | Area, m² |
| $\Delta S$ | Change Entropy, kJ / kg K in |

Subscript

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

Greek letters

| Symbol | Description |
|--------|-------------|
| $\alpha$ | Absorptivity |
| $\tau$  | Transmissivity |
| $\eta$  | Efficiency |