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A SINGLE-EFFECT SOLAR STILL FOR DESALINATION OF TREATED OIL PRODUCTION WATER

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ABSTRACT

Methods for evaporating oil produced water (OPW) have been tested and used to remove salinity by means of solar energy. The aim of the present study was to assess the application of a conventional solar still in the desalination of treated OPW, investigating the temperatures reached and comparing them with solar radiation levels. The solar distillation equipment consisted of a two-water single effect passive solar still. The still was fed with treated OPW. Temperatures were recorded using data loggers with PT100 sensors. The experiments were conducted between February and April 2008. The temperatures obtained are consistent with the type of still used and the seasons of the year. The maximum recorded temperatures varied between 49.9 °C and 63.8 °C. The distilled volume ranged between 48 and 240 mL/h. The estimated daily amount produced was compatible with literature values. The results show that the single-effect solar still can also be used to desalinate treated OPW.

KEYWORDS

oil produced water; solar energy; solar still; solar radiation; saline water

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1. INTRODUCTION

Large volumes of oil produced water (OPW) are generated during oil exploitation **(Henderson *et al.*, 1999; Thomas, 2001)**, mainly in mature fields **(Galvão *et al.*, 2006; Neff *et al.*, 2006)**. To comply with increasingly rigid legislation and to limit the use of natural resources, physical-chemical processes are needed to treat the waters produced. The resulting increased costs for chemical products and the production of undesirable waste require more ecologically friendly alternatives for this purpose, such as advanced oxidation processes (AOPs).

According to **Campos and coworkers (2002)**, OPW is a very complex type of fluid. Its characteristics and properties are quite variable owing to the geological formation and geographic location from which they originate, in addition to the possible oil recovery methods used, as corroborated by **Bader (2007)**. Salinity is a common characteristic of these waters that can reach salt levels higher than 80,000 mg/L, hindering the implementation of biological treatment and AOPs **(Kormann *et al.*, 1991; Pignatello, 1992; Sirivedhin and Dallbauman, 2004)**. Methods for OPWs have been tested and used to remove the salinity, using conventional energy sources **(Schuhli, 2007)**. The aim of the present study was to assess the application of a conventional solar still in the desalination of treated OPW with low oil content, investigating the temperatures reached and comparing them with solar radiation levels. A literature review indicated the existence of several types of solar stills **(Bouchekima, 2002; Delyannis, 2003; Fuentes and Roth, 1997; Tiwari *et al.*, 2003)** and the temperatures and outputs that they have attained. Design modifications have been proposed to enhance the productivity of distilled water **(Tanaka and Nakatake, 2006; Abdallah *et al.*, 2008)**. The modification proposed is the use of a glass cube at the base to avoid sample contamination, given that the peculiar characteristic of containing organic elements along with salt causes OPWs to react with the compounds that give the base its black coloration, in addition to their aggressive and corrosive nature. It is believed that using glass coating may result in some temperature loss.

2. CHARACTERIZATION OF THE STUDY ENVIRONMENT

The city of Natal, capital of Rio Grande do Norte (RN) State, in Northeastern Brazil, has an average of 300 days of sunshine per year. Because of its proximity to the equator, it has high sunlight levels (average of 5000 W/m^2d), according to INPE (National Institute of Space Research). However, the prevailing winds cool the still's cover. The RN State is the third largest producer of oil in Brazil and the first in onshore production, but its fields are mature and contain heavy oils, which generate large volumes of OPW. The mixture of water from different producing fields gives rise to low-salinity water if compared to other OPWs. The unit that receives and treats this effluent is located in the town of Guamaré, in the RN State.

3. EXPERIMENTAL PROCEDURE

The solar distillation equipment consisted of a two-water passive single-effect solar still. The still measures 0.94 m × 0.02 m × 0.05 m at the basin, comprising a 1 mm-thick aluminum box coated with an equal-sided glass cube, painted in black. The still cover has a tilt of 20° (the recommended angle for the latitude of Natal), forming an isosceles triangle prism and two equal lateral surfaces; the hypotenuse surface is hollow and faces the base of the equipment. The still used in this study can be seen in Figure 1 and its schematic is shown in Figure 2.

The experiments were carried out at the Federal University of Rio Grande do Norte (UFRN) campus in Natal (5°47'42" and 35°12'32"), at a facility called the Solarium. The still was fed with treated OPW, whose characteristics are shown in Table 1.

Batch feeding was used to feed the sample on the still and continuous feeding was devised to obtain the distillate. During the experiments the temperature was monitored at four points on the still: base water (1), steam (2), distillate trough (3) and inner glass temperature (4).

The temperatures were measured using Novus LogBox AA data loggers with stainless steel

Figure 1. Photograph of the solar still used in this work.

sheathed PT100 sensors. The temperatures were measured every 10 min. The sunlight data were acquired directly from the INPE web site (www.inpe.br). The data were collected at the climatology station of that institute in Natal, located around 2000 m from where the experiments were carried out.

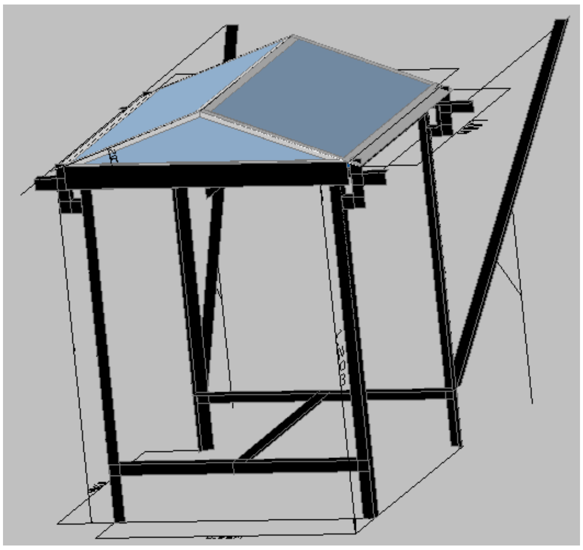

Figure 2. Schematic of the solar still used in this work.

The experiments were conducted between February and April 2008, a period that includes the end of summer and beginning of fall in Brazil and the end of the hot and sunny period and beginning of the rainy and cooler temperatures in the Northeast.

Table 1. Characteristics of OPW (average values).

Parameter	Value
pH	8.32
Conductivity (μS/cm)	3,990.00
Chlorides (mg/L Cl)	700.00
Turbidity (NTU)	52.00
Color (PtCo)	61.50
Sulfates (mg/L SO_4)	134.83

4. RESULTS AND DISCUSSIONS

The temperatures obtained in the study period are compatible with the type of still used and time of the year. Figure 3 shows the temperature results obtained in the experiments. The figure shows that the maximum temperatures varied between 49.9 °C and 63.8 °C on experiments 1 and 6 (in the months of February and March), respectively, and are consistent with solar radiation levels recorded on these days, as shown in Figure 4.

Figure 5 shows the sensitivity of the system inside the solar still when subjected to climatic

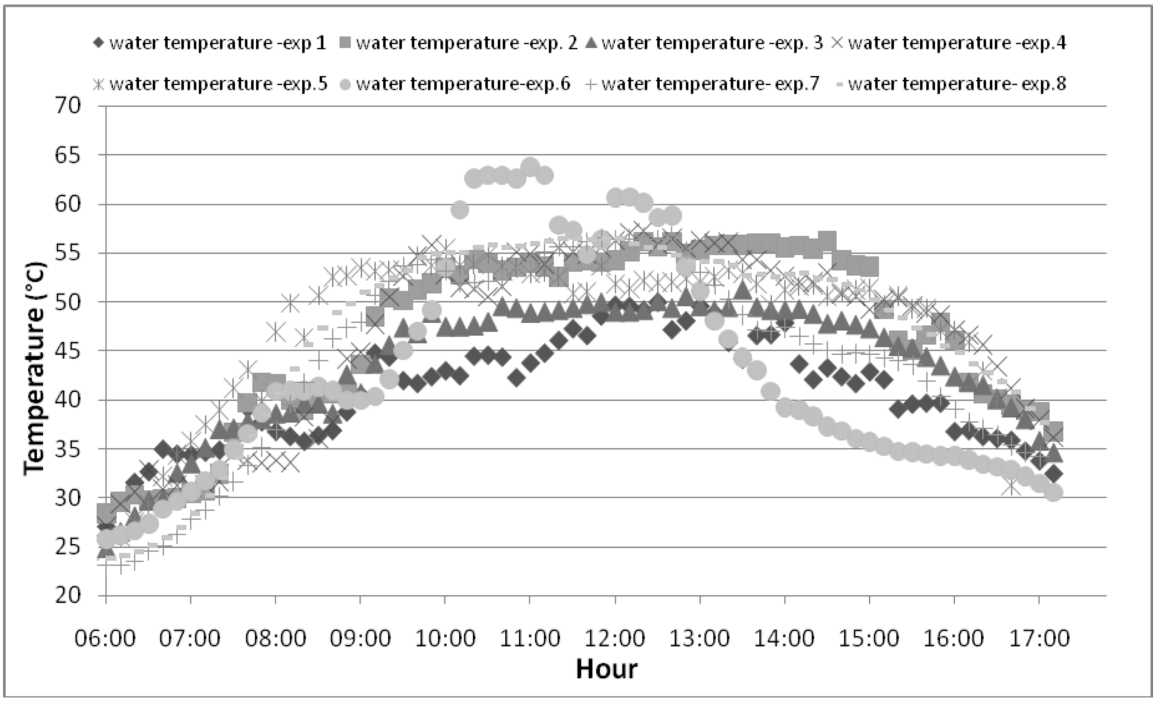

Figure 3. Temperatures obtained in the experiments.

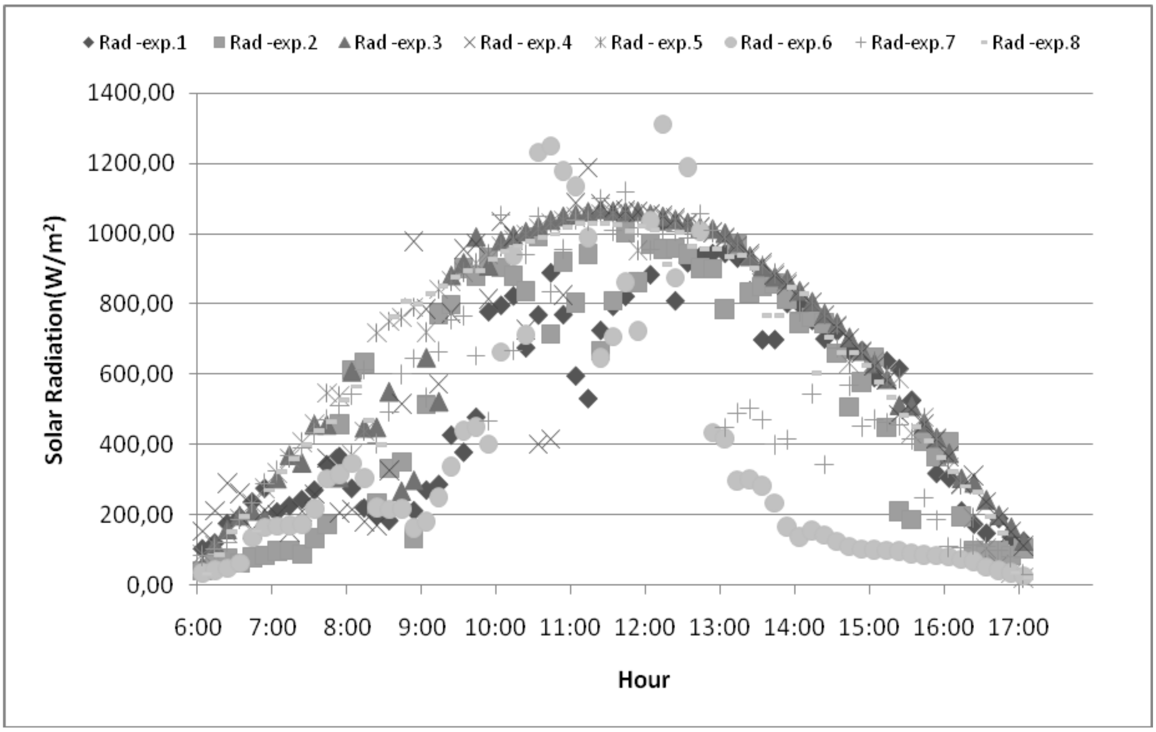

Figure 4. Solar radiation intensity in W/m^2 – source: INPE.

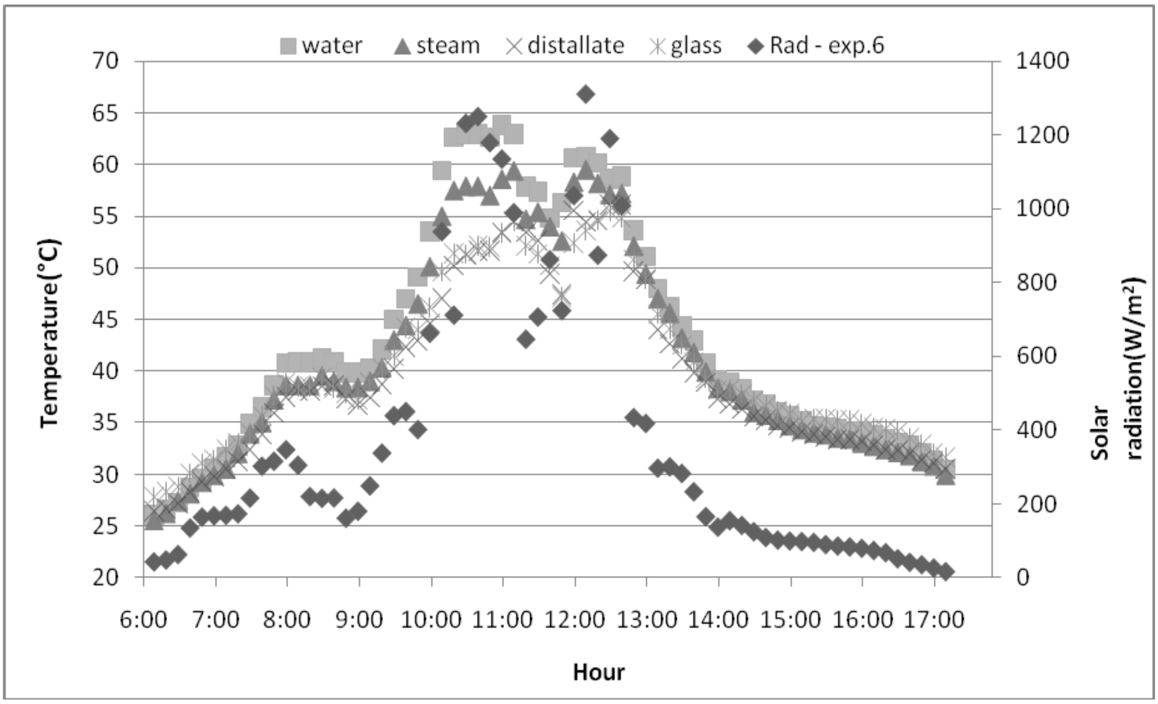

Figure 5. Solar radiation levels and water, steam, distillate and glass temperatures.

variation. It is worth highlighting the particular results of experiment 6, in terms of the indices of incident solar radiation, corresponding to the highest temperatures.

Figure 6 shows the remaining climatic parameters that affect the still performance. The same configuration can be observed: instead of a parabolic shape, the curve of temperatures inside the equipment was M-shaped, similar to the sunlight curve on the day of the experiment. It should be pointed out that climatic variations involve sunlight, cloudiness, wind velocity and humidity. Of all these parameters, solar radiation and cloudiness are closely related, and even though solar radiation varies with the time of year,

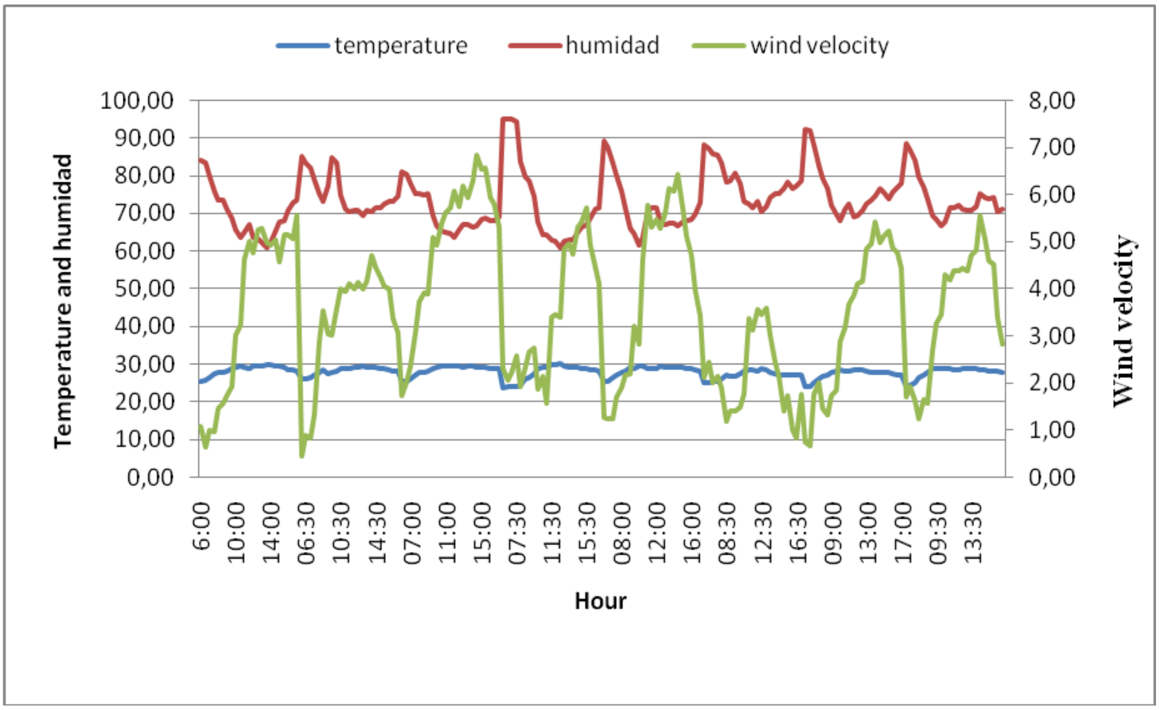

Figure 6. Variation in ambient temperature, humidity and wind velocity in the study period.

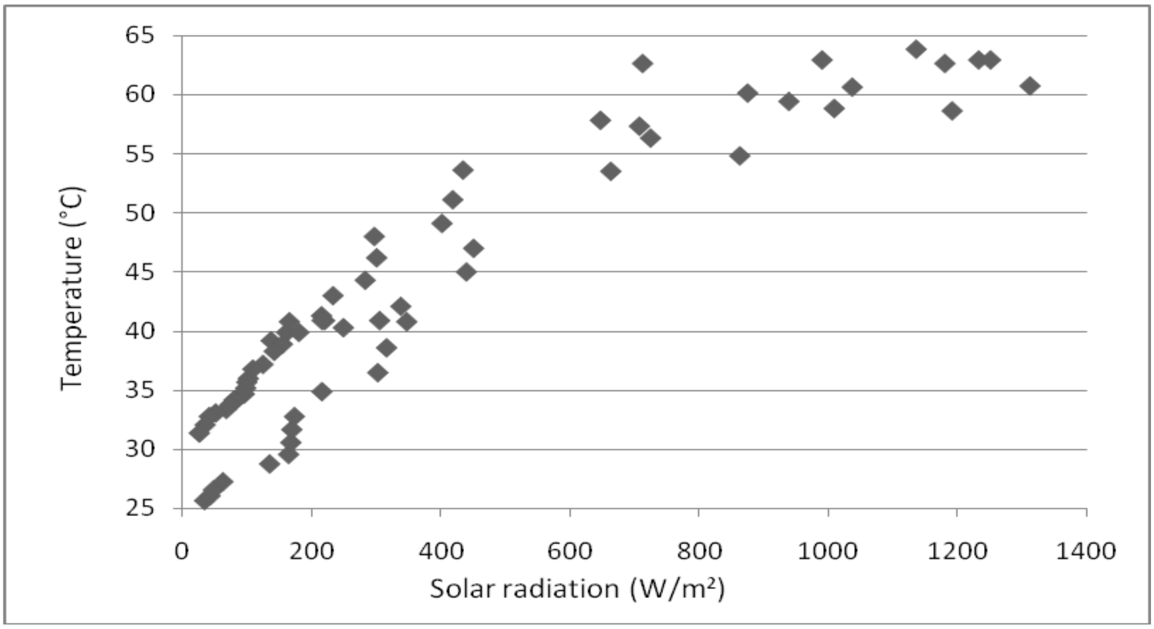

Figure 7. Water temperature as a function of radiation levels.

geographic position, and the presence of clouds, it changes the direction and the wavelength of sunlight, which in turn transforms from direct to diffuse **(Duffie and Beckman, 1991; Bird *et al.*, 2004)**. During the study period the wind velocity ranged between 3.46 and 6.84 m/s for the maximum daily values (between 12 p.m. and 2 p.m.) and between 0.44 and 1.73 m/s for minimum values at the coolest times of the day (around 6 a.m.), as shown in Figure 6. Figure 7 shows the water temperature variation as a function of radiation levels.

The experiment carried out on March 26th, 2008, showed the least uniformity in the rise and decline of solar radiation and, consequently, in temperatures, owing to the effects of cloudiness. Figures 8 and 9 show the temperature profiles for that day with the lowest temperatures and their relationship with incident radiation.

The sensitivity of the system in terms of climatic conditions is once again displayed, given that the very different conformations in temperature and

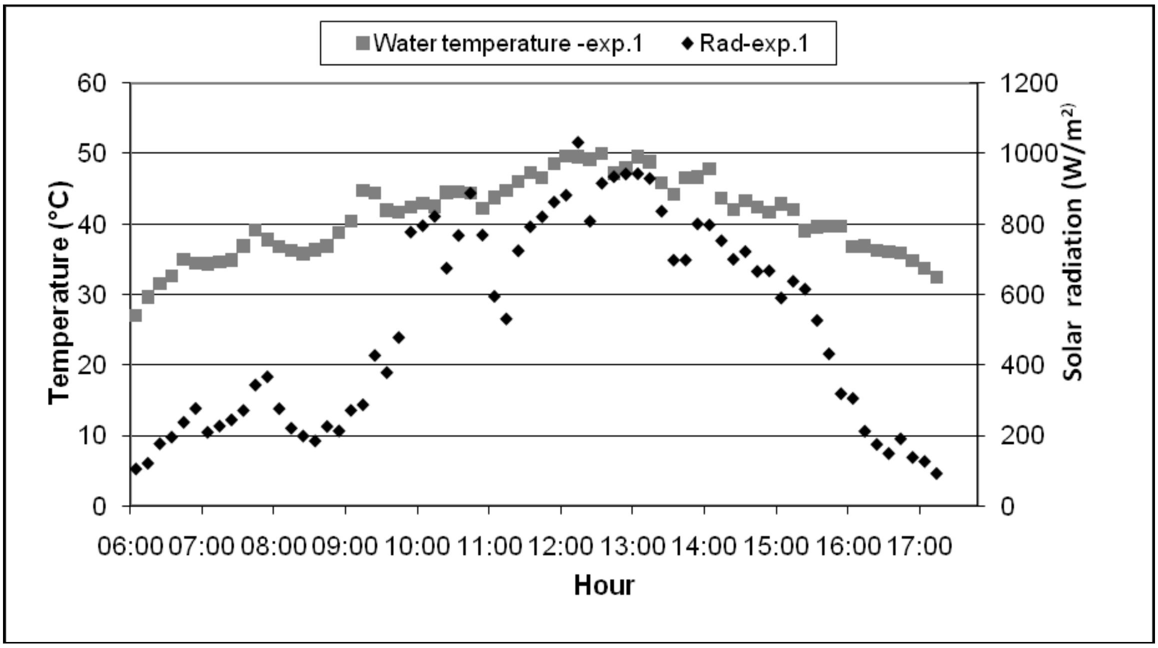

Figure 8. Temperature variation and radiation levels in the experiment carried out on March 26^{th}, 2008.

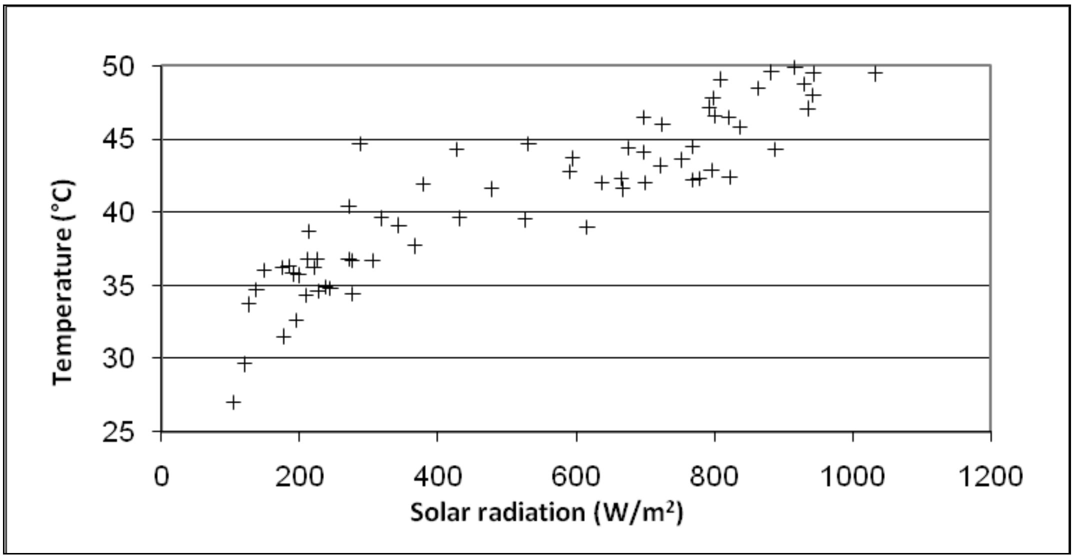

Figure 9. Water temperature variation as a function of incident radiation.

sunlight are similarly observed in the temperature graphs as a function of radiation.

The uniformity in solar radiation can be seen in Figure 10. On the other hand, it can be observed that steam temperature remained higher than that of the water at the coolest times of the day, from which it can be assumed that the heat received was not being accumulated.

This inversion between water and steam temperatures may indicate that the base was not absorbing heat, which could be due to the accumulation of salts in the cube.

In addition to the temperature and radiation results for the study period, the volume distilled per hour was sporadically measured, and ranged between 48 and 240 mL/h for the coolest (8 a.m.) and hottest (12 p.m.) times of the day. An estimate of the daily amount produced showed that it was consistent with literature values **(Neff *et al.*, 2006)**.

The experiments conducted showed that, as expected, the highest temperature peaks coincide with the highest sunlight peaks. The highest water temperature was recorded at the moment of greatest solar intensity, even though on this

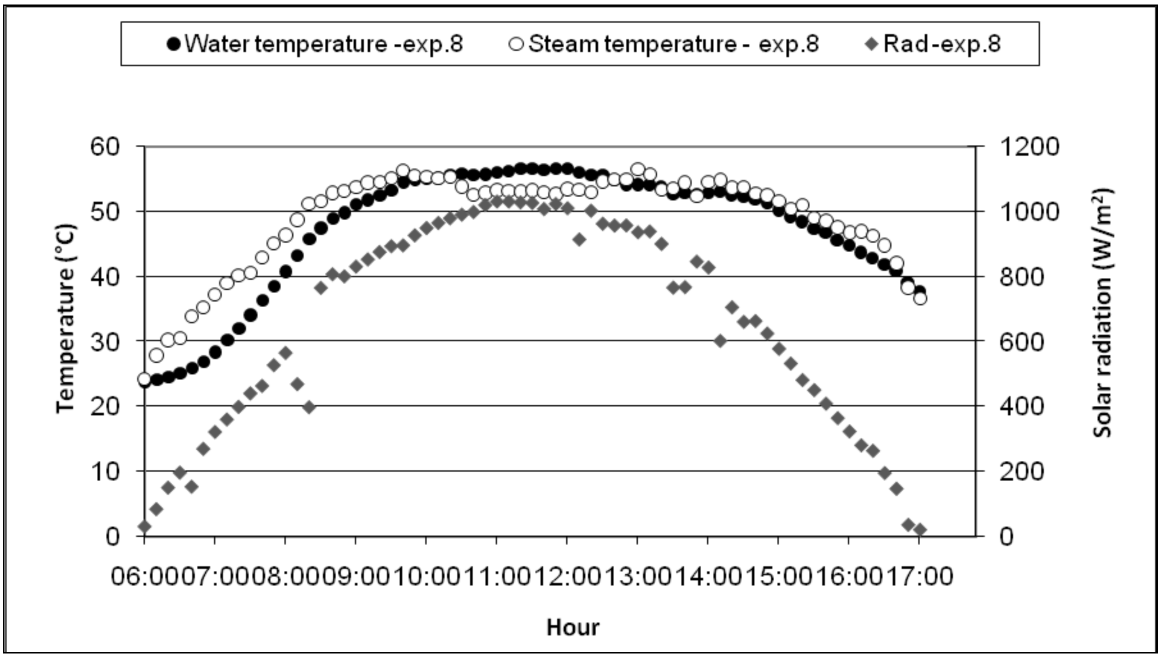

Figure 10. Water and steam temperatures and radiation levels as a function of time.

specific day the sunlight levels were affected by several periods of cloudiness with consequent lowering of water temperatures at the base of the solar still. Furthermore, the equipment was sensitive to climatic variations, given that it was unable to maintain energy and temperature under unfavorable climatic conditions. On the other hand, the system recovered rapidly when the climatic conditions were once again favorable; that is, high direct sunlight, low cloudiness and humidity.

5. CONCLUSIONS

The results show that the single-effect solar still can also be used for the desalination of treated OPW.

Using OPW glass at the basin promoted a slight decline in energy efficiency, although not compromising the equipment performance, given that the presence of glass at the basin altered the refraction and reflection levels of sunlight. In the experiments performed, the temperatures obtained and the volumes of the distillate were compatible with the results of solar stills reported in other studies **(Abdallah et al, 2008)**. It should be pointed out that most of the experiments occurred during the rainy season, under high cloud levels, and involved the use of such a complex effluent as OPW.

Another important factor is that the analysis made with the distillate showed that removal of salts is compatible with distillation of common water, the values of chlorides and sulfates in distillate are at least than 2 mg/L and zero, respectively. The corresponding salt removal from the studied samples reached values greater than 90% for two salts.

Thus, based on the climate of the region and its energy potential, we conclude that the use of solar stills in the treatment of effluents has a promising future. The equipment must be optimized to store heat during times of low radiation, whilst respecting the volume limits and the technical features of the area.

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