Evaluation of solar still depending on air velocity conditions

Margarita Castillo Téllez[1], *Beatriz Castillo Téllez[2], Beatriz M. Aponte Castillo[3], Luz María Hernández Cruz y Andrea R. Cruz[1]

[1] Facultad de Ingeniería, Universidad Autónoma de Campeche/Campeche, México

[2] Centro Universitario del Norte, Universidad de Guadalajara/Colotlán, Jalisco

[3] Unidad Profesional Interdisciplinaria de Biotecnología, Instituto Politécnico Nacional, CDMX, México

*Corresponding author

Abstract

In solar distillation, the production of distilled water is a function of efficient design involving evaporation-condensation processes under variable operating conditions, such as solar irradiance, temperature, wind speed and direction, and thermodynamic parameters characteristic of the solar still type. The experimental results of the effect of air velocity in different modifications made on the double shed of the solar still on the productivity of distilled water under controlled conditions are presented. The study was conducted in Temixco, Morelos, Mexico, at 18º 54' north latitude and 99º 13' west longitude, with an average daily solar irradiance of 750 W/m^2. It was observed that under average daily irradiation conditions of 5.1 kWh/m^2, the still, cooled with a wind speed of 5.5 m/s, can produce 0.76 l in the case of confinement, or 0.66 l in the case of non-confinement of ambient air.

Keywords: Double slope solar still, Natural and forced convection, Wind tunnel, Energy efficiency.

1. Introduction

One of the most significant problems humanity faces is the supply of drinking water. Water desalination is a crucial solution to provide safe water and meet the world's growing population (Bamasag et al., 2020). However, the most widely used technologies for desalinization are highly intensive in energy consumption, such as thermal energy (evaporation) and electricity (compression and reverse osmosis). The current energy situation demands saving and efficient energy use and sustainable development. A viable option is to use renewable energy through solar water distillation. Its basic principle is the greenhouse effect: the sun heats an air chamber through the transparent glass; at the bottom, we have standing water to distill (García Valladares et al., 2017). Depending on solar radiation and other factors: such as wind velocity (which cools the outer glass), a fraction of this water evaporates and condenses on the inside of the glass, which is inclined; this inclination is fundamental to prevent it from coming back. the condensed waterfalls into the tray that contains the water to be distilled, so that the drops fall on a channel that collects said condensate (Castillo Téllez and Pilatowsky-figueroa, 2013).

In the case of double slope solar stills (DSSS), the influence of the different parameters on productivity (l/day) has been theoretically and experimentally analyzed. In the case of the effect of air velocity, this is an essential parameter that has a significant influence on the production of distilled water, especially on the cooling of the glass cover (condensate surface). A fraction of this water is evaporated and condensed in the glass cover, which is inclined, so that the drops fall into a channel that collects said condensate, preventing them from falling back to the lower sheet in the condensation process brine (Castillo-Téllez et al., 2015).

In the case of double house solar stills (DSDC), the influence of the different parameters on productivity (l / day) has been theoretically and experimentally analyzed. In the case of the effect of air velocity, few theoretical and less experimental works have been developed, and the reported conclusions do not coincide, sometimes contradictory. In the solar still, the amount of condensed water depends on the velocity and temperature of the ambient air, which vary throughout its operation, making it difficult to quantify the influence of each of them, first with the condensation capacity and finally with the thermal efficiency. In addition, the climatic parameters (air velocity, ambient temperature, irradiance, and relative humidity) cannot be controlled; therefore, it is complicated to determine the distilled water that can be obtained. In the case of different ambient air velocities: specially to achieve a homogeneous distribution on the condensation surface of the still.

Among the authors who have analyzed this effect theoretically, a theoretical study was carried out that predicts the productivity of a DSDC under different climatic, design, and operational parameters, concluding that an increase in velocity from 1 to 3 m/s results in 8% higher productivity (Al-Hinai et al., 2002). Regarding the works where an

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opposite effect or little influence of the air velocity is obtained, the different parameters that affect single slope solar performance are still analyzed in a study. It is concluded that as wind speed increases, distilled water production gradually decreases and when a change of 1 to 9 m/s occurs, productivity decreases by 13% (Rubio-Cerda et al., 2002). In another study, a mathematical model validated by an experimental work for a DSCS is proposed, and it is concluded that the wind velocity has a negligible effect on the production of water when increasing the velocity from 0 to 9 m/s; this increases a 10% (Nafey et al., 2000). In conclusion, few theoretical and experimental works have been developed, and the reported conclusions do not coincide, sometimes contradictory. Therefore, in this work, all efforts were focused on analyzing the conditions that still affect the operation of double house solar and its relationship with the influence of ambient air.

2. Materials and Methods

2.1 Experimental prototype

Experimental equipment consists: of two DSSS, each containing a copper tray, is square in shape, 16 gauge (0.5 m x 0.5 m x 0.05 m) with a maximum volume of 12.5 l of water to be distilled, with matt black paint resistant to high temperatures, with a catchment area of 0.25 m^2. Both transparent covers are made of glass (3 mm thick) with a 23º inclination. The sidewalls and the bottom were thermally insulated with polyurethane foam thickness of 0.10 m. The liquid level to be treated is kept constant (2.5 cm). The amount of distilled water is recorded continuously, with a precision scale.

In the part where the two glass covers (booth) are recharged on the tray, there are two aluminum channels to which a slight slope and a ¼ inch hole were machined, which are the collecting and transport means of condensate. In the central part of the DSDC, a container distributes the water to the stills, maintaining a constant level of brackish water to be treated. Each still has an independent condensate collector, where distilled water is continuously recorded. The still was built with an orifice on one side to feed the tray with a ¼ inch hose with the water distilled. At the base, another ½ inch hole was located, used to eliminate the brine.

Instrumentations. For the temperature records, type K thermocouples were used, and the data were acquired daily using a Campbell Data Logger. These thermocouples have a calibration curve provided by the manufacturer and do not require additional calibration. They are coupled to the selected data logger; it correlates with voltage and temperature through a program that integrates the manufacturer to the data acquisition system.

A Tor-Rey electronic scale, model L-EQ 5/10, was used to determine the distilled water produced, with an accuracy of 0.01 kg; in the graphics on the distilled water production, you can see the error bars for this accuracy mentioned.

For the distribution and control of air velocity, four scenarios were proposed, which allow finding a relationship between wind speed and the increase or decrease in productivity: 1) Natural convection, 2) Natural convection and with acrylic cover, 3) Forced convection, fans in series with a double slope, 4) Forced convection, fans in series and without a wind tunnel. Comparison of the productivity of these scenarios allowed correlating the influence of air velocity and temperature. Three fans of dimensions 119 x 119 x 38 mm were used to achieve the necessary rates to simulate different climatic scenarios, with a nominal voltage of 48V.

Figure 1 shows the experimental device in its various studied settings.

Fig. 1: DSSS in operation: 1) Natural convection, 2) Natural convection with acrylic cover, 3) Forced convection, fans in serial and double slope, 4) Forced convection, fans in serial and without wind tunnel

Daily meteorological information was acquired: solar irradiance, ambient temperature, wind speed and direction, and relative humidity, continuously recorded at the Renewable Energy Institute (IER) in Temixco, Morelos, Mexico. Tables 1 and 2 show the accuracy and description values given by the manufacturers of the different sensors used in this solarimetric station.

Tab. 1: Accuracy of the measuring instruments (given by the manufacturers)

Sensor	Maximum error (manufacturer)
Solar radiation	±0.5 W/m^2
Ambient temperature	±0.4 °C
Relative humidity	±3%
Wind speed Wind direction	±0.5 m/s ±5°

Tab. 2: Characteristics and description of the measuring instruments provided by the manufacturers.

Variable	Descripción	Modelo	Calibración
Global irradiation	Pyranometer Eppley	PSP	Anual (IGF-UNAM) (K=7.68 Sensor Campbell
Ambient temperature and RH	Sensor Campbell, CS500	1000 ΩPRT, DIN 43760B	Bianual (manufacturer)
Velocity and wind direction	Wind Sentry mod 03002-5 R.M. Young Company	03002-5	Biannual (manufacturer)

2.3 Experimental procedure

The brackish water distribution container is supplied during the night to ensure the water supply to each still for its operation during the day, keeping the level in each constant at 2 cm through the continuous level burette. The variations of the temperatures inside and outside of the still, brackish water, environment parameters, solar radiation, and the selected velocity inside the wind tunnel are recorded. The distilled water is measured by recording its weight on the precision mentioned above balance. The measurement cycles are taken at 8:00 p.m. each day; at the beginning, the average air velocity is set, and the variations of the different parameters are recorded using an automatic data acquisition system. The covers are cleaned beforehand to prevent some particles from the environment from settling down and reducing their transmittance. Discussion and results

Figures 2 show the behavior of the average weather conditions corresponding to the test period, as a typical example of what can be expected in the locality where the study was carried out. A maximum ambient temperature of 28 °C was observed, while the minimum value was approximated at 7:00 a.m. Concerning the solar irradiance, measurement time shows a peak at 1:00 p.m. with a magnitude of 732 W/m^2. Regarding the relative humidity, it can be seen that the maximum value is 50%, while during sunny hours, the average was 30%.

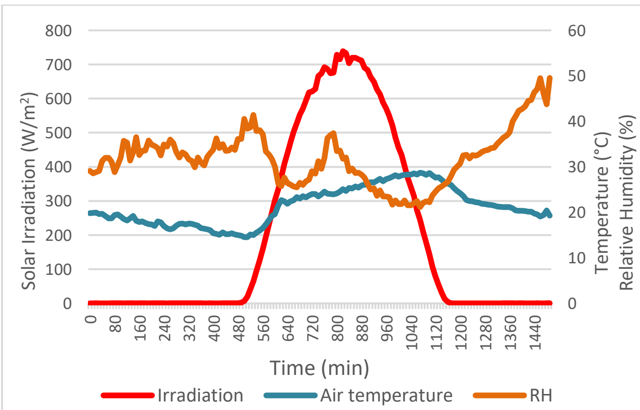

Fig. 2: Irradiance, ambient temperature and relative humidity recorded by the solar station

3.1 Natural convection still

To determine the effect of forced convection in the efficiency of a solar still, it was necessary to resolve the thermal performance of the still without the convection device. Figure 3 shows the temperatures obtained in the still with natural convection and the distilled water obtained as a function of the energy received in the collector (kWh) during five consecutive days of testing.

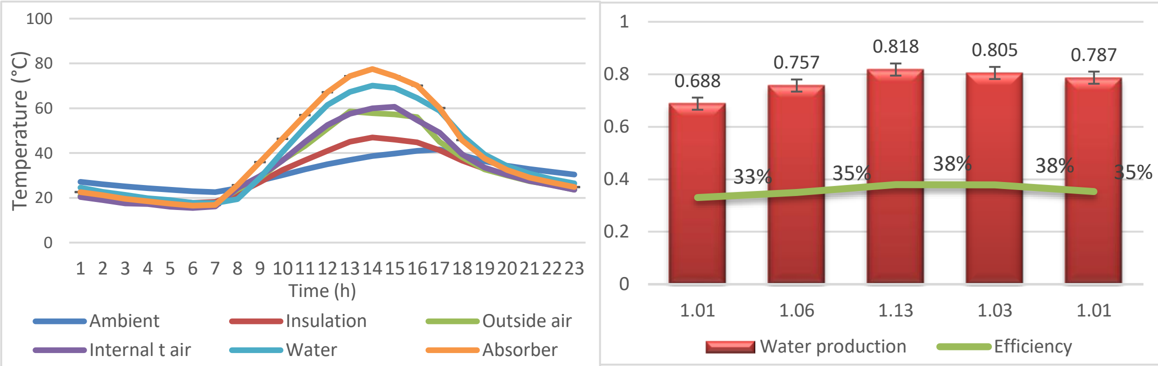

Fig. 3: Measured temperatures inside and outside of the Natural convection still and the distilled water obtained (l) as a function of the solar energy received by the still (kWh).

It is observed that the temperature between the interior and exterior glass are practically the same, reaching a maximum of 58 °C. However, the absorber temperature reaches a maximum of 77 °C, while the water surface temperature reaches 69 °C. It can also be observed in the bar graph that the distilled water obtained during the five consecutive days that were taken as a reference concerning the energy received in the collector (irradiation per collector area by the factor 0.814 derived from the attenuation of the cover glass), to analyze the behavior of the still with natural convection and have a comparison with other proposals presented in this work. It is also inferred that for average irradiation of 4.97 kWh/m^2, it still has an average production of 0.74 l. The highest volume of distilled water obtained was 0.82 liters for irradiation of 5.5 kWh/m^2.

3.2 Natural convection still with acrylic cover

To analyze the effect of placing the acrylic cover in the still with natural convection, Figure 4 shows the temperature profile in the still and the water obtained 5 consecutive days of testing.

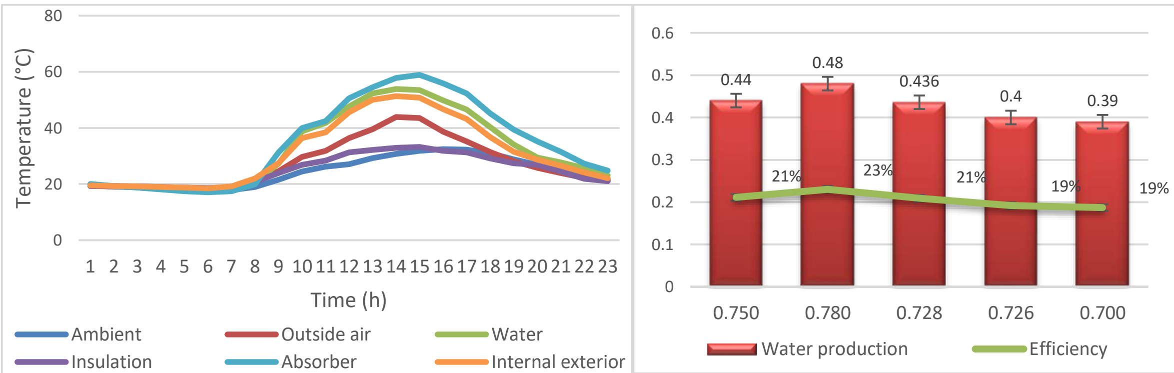

Fig. 4: Measured temperatures inside and outside of the Natural convection still with acrylic cover and the distilled water obtained (l) as a function of the solar energy received by the still (kWh).

It can be observed that a maximum temperature in the absorber of approximately 60° C is reached, with irradiation of 4.5 kWh/m^2.

The obtaining of distilled water drops considerably highest than in the others cases because the percentage of irradiance that reaches the absorber and heats the water is lower due to the obstruction of this light beam due to the double cover: acrylic plus glass, both with a thickness of 3 mm. The correction factor due to the attenuation of the glass cover plus the acrylic cover is 0.66. Therefore, it is concluded that having a double cover lowers the still's performance by approximately 34%. The highest volume of distilled water obtained was 0.48 liters for solar energy received in the collector of 0.78 kWh, corresponding to a solar resource of 4.7 kWh/m^2.

3.3 Forced convection still with fans in serial and double slope

To increase the convection phenomenon on the DSSS glass slope, a 3.0 mm thick acrylic sheet with a visible optical transmission of 80.7% was placed over the covers to create a "wind tunnel." Three fans were placed in series in such a way that sufficient care was taken that the speed of the air injected by the fans was uniform over the entire roof surface and at different average wind speeds: 2.5, 3.5, and 5.5 m/s. The results of obtaining distilled water with the previous conditions are shown in table 3.

Table. 3: Results of the still with forced convection.

Collecting data date	Wind speed (m/s)	Average irradiance recieved (kWh/m^2)	Solar energy received (kWh)	Distilled water obtained (l/day)
July 24	2.5	5.22	0.860	0.61
July 2	3.5	5.18	0.854	0.75
August 2	5.5	4.91	0.810	0.76
September 13	6.9	5.10	0.842	0.62

During the days in which the experiments were carried out, the solar resource measured in the meteorological station was 5.1 kWh/m^2; the variation in obtaining distilled water will only be assigned to the forced convection produced by the increase in air velocity. Under these conditions, the absorber, water, and indoor air temperature decreased from 69 ºC, 65 ºC, and 63 ºC to 50 ºC, 49 ºC, and 49 ºC, respectively. In general, it was determined that as the air velocity over the outer cover increases, the convection phenomenon increases, decreasing the temperature of the glass cover from 51 ºC (v = 2.5 m / s) until reaching a value equal to the ambient temperature (v = 5.5 m/s). In this interval, the distilled water obtained is increased due to an increase in the condensation rate; this has the consequence: obtaining of distilled water increases until reaching a maximum value, which is obtained when the temperature of the outer cover is almost equal to that of the environment, and from there, the production decreases derived from the fact that the glass cover is colder than the environment.

3.4 Forced convection still with fans in serial and without wind tunnel

Measurements were carried out with the implementation of forced convection but without the wind tunnel to compare the natural action of the wind on the solar still; the speed at which the fans worked under these conditions was 5.5 m/s because, at this velocity, the highest production of distilled water was obtained in the previous scenarios.

In this case, the distilled water obtained was 0.66 l with irradiation of 4.01 kWh/m^2, while the solar energy received in the collector was 0.816 kWh. For forced convection with the same air velocity (5.5 m/s) and solar energy received in the collector with similar values (0.816 kWh in this case and 0.81 kWh in table 3), the water production is 13% less than the one obtained when the air is confined in the double cover (figure 5).

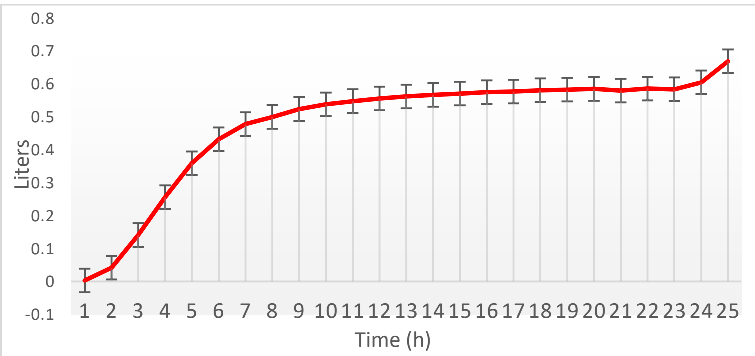

Fig. 5: Obtaining accumulated distilled water on forced convection still with fans in serial and without wind tunnel

In this case, the distilled water obtained was 0.66 l with irradiation of 4.01 kWh/m^2 (value measured in the meteorological station), while the solar energy (Es) received in the collector was 0.816 kWh. To compare the values in table 3 for forced convection with the same air velocity (5.5 m/s) and solar energy received in the collector with similar values., the water production is 13% lower than obtained when the air is confined in the double slope.

In analyzing the efficiency of a solar still, geometric parameters and those related to the materials' properties are involved. In the case of the double slope solar stills, the influence of these parameters on efficiency and productivity has been analyzed theoretically and experimentally. The efficiency of the Still (η) is calculated with the following expression (Cooper, 1973):

$$\eta = \frac{(V * hfg)}{(P_{prom)} * H * 3600)} \; ; \; \eta = \frac{(V * hfg)}{(I_{prom)} * h * 3600)} \qquad \text{(eq. 1)}$$

In the previous expression:

- V, is the volume of distillate (measured in liters, taking into account that one liter of water has a mass of 1 kg),
- Hfg, is the latent heat of vaporization with units of J/kg, whose value was obtained taking into account the maximum temperature obtained in the water to be distilled,
- P, is the power of the solar radiation that falls on the absorber surface (given by the product of the average irradiance I of the day measured in W/m^2 with the surface S of the collector measured in m^2),
- H, time exposure in hours (sunshine hours).
- The PxHx3600 product is the solar energy captured by the absorber expressed in Joule.

Table 4. It shows the efficiency of the DSSS with Natural and Forced convection in the conditions of this analysis.

Day	Velocity (m/s)	Es (kWh)	V (l)	Hfg (MJ/kg)	η (%)	Study case
02-ene	0.00	0.854	0.56	2.366	43.1	Natural convection, without double cover
09-ene	0.00	0.823	0.57	2.366	45.5	Natural convection, without double cover
09-jun	0.00	1.01	0.688	2.366	44.8	Natural convection, without double cover
09-jul	0.00	0.78	0.48	2.342	40.0	Natural convection with double cover
24-jul	2.50	0.86	0.61	2.354	46.4	Natural convection with double cover
02-jul	3.50	0.854	0.75	2.378	58.0	Natural convection with double cover
02-ago	5.50	0.81	0.76	2.39	62.3	Natural convection with double cover
06-feb	5.50	0.816	0.66	2.39	53.7	Forced convection without double cover
13-sep	6.90	0.842	0.62	2.39	48.9	Forced convection with double cover

3.5 Conclusions

In the present experimental work, the results of the analysis of the convective effect of air velocity on obtaining distilled water in a double house solar distillation system were presented. The air velocity domain was established from 0 m/s to 6.9 m/s, observing that an airflow that increases the convection phenomenon on the glass cover increases the efficiency of the still. The results obtained show a correlation between the wind speed on the glass cover and the obtaining of distilled water. It was found that under the same climatic conditions, forced convection in the speed range of 2.5 m/s to 5.5 m/s helps to increase the amount of distilled water obtained and increases the efficiency of the still, obtaining a value maximum of 62.3%. Under conditions of average daily irradiation of 5.1 kWh/m^2, the DSSS with an area of 0.25 m^2, cooled with a wind velocity of 5.5 m/s, can produce 0.76 l in the case of confinement, or 0.66 l in the case of non-confinement.

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