Desalination using a parabolic-trough concentrator

Article *in* Applied Solar Energy · October 2012

DOI: 10.3103/S0003701X12040081

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ISSN 0003-701X, Applied Solar Energy, 2012, Vol. 48, No. 4, pp. 254–259. © Allerton Press, Inc., 2012.

Desalination Using a Parabolic-Trough Concentrator[1]

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Received July 4, 2012

Abstract—There are presented desalination results by using a parabolic-trough concentrator (PTC) device of 5.5 m^2, 0.7 m of line focal distance and aligned in the East—West direction. The length of the PTC is 2.5 m and its rectangular absorber cavity has 1m length made of black aluminum. The equipment is located in Cocayalta (48 km from Lima, with 700–850 W/m^2) and there were made simple modifications on the cavity to increase the fresh water production, from 3250 cm^3 (3.25 liters) using the simplest model to 6360 cm^3 (6.36 liters) with the thermal insulation and wind protection model, that represents an increase of about 95%. Finally, water analysis showed a good quality of the fresh water obtained.

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INTRODUCTION

Water scarcity in Peru is a serious human health problem, like as in many countries around the world. Andean and Amazonian regions represent about 90% of total extension of the country, with no problem of fresh water, however about 75% of population (more than 20 million) lives in the Coastal region (due to historical and economical factors) which is arid in spite of be located in a tropical region (from 0° to −18° latitude). To mitigate this problem there are three main alternatives: mining on occidental mountains looking for water reservoirs, reusing treated waste water, and sea water desalination, but neither of them were been implemented yet. Furthermore, northern coast receive a solar radiation intensity mean of 900 W/m^2 around 300 days a year, at Sechura desert (one of the driest in the world), then these are very good conditions to investigate low cost desalination using solar energy.

The solar technology is investigated from many decades ago, but in recent years costs of solar desalination devices were reduced and efficiency was increased. Depending on materials and geometry used, fresh water is produced from 1 L/m^2 by the most simple models to 20 L/m^2 by the most sophisticated ones [1], and performances varied from 30% to 60%, respectively [2]. The last one corresponds to combined solar technologies with low cost investment [3]. Generally, investigations were oriented to study the water production depending on solar intensity, sea water depth, ambient and water temperature, basin geometry, thermal materials, etc. [4]. Experimental tests under a solar intensity about 1 kW/m^2 (~6 kW h/(m^2 day)) showed productions of 1.4 L/m^2 (in a single fixed solar still model), 1.8 L/m^2 (single solar still with sun tracking system), 1.8 L/m^2 (fixed solar still with mirror), 4.3 L/m^2 (fixed solar still with step wise) and 5.2 L/m^2 (solar still with step wise and sun tracking system [5]). All of the devices mentioned previously are more efficient if they use preheated sea water by solar concentrators, for example, using a plane collector with heat absorber materials, production is increased in 36% [4]. Also, it was reported a production of 12 L/m^2 by using plane collectors with vacuum tubes, representing more than 60% of thermal efficiency [2], or a production of 11 L/m^2 by using a multi-stage distiller with evacuated plane collector [6].

The low efficiency of all solar desalination devices is mainly due to the heat loss because the big area of the collector. However, it is not the case of parabolic-trough concentrators because they have a less area where heat could be lost. For this reason these devices can reach high temperatures and are also used to generate electricity [7], additionally with a lower cost than other solar collectors [3].

In this paper a PTC is investigated as a distiller device, aligned on East–West orientation to avoid the use of solar tracking system, and using the simplest and cheapest materials.

EXPERIMENTAL SET-UP

The PTC distiller has a solar concentrator made of two high reflectance aluminum sheets (2.5 m × 1.25 m × 0.4 mm each one) installed over a series of curved wooden structure, all of them fixed on a metallic structure. As a result, it was obtained a surface with a profile given by $y = x^2/4p$, x and y are the parameters shown in Fig. 1.

The parameter p is the distance from the vertex to the focus of the parabola. Its value was chosen in 0.7 m because it is desired that $p > y(x_2)$ being $x_2 = 0.11$ m the

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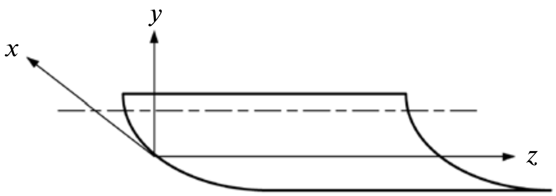

Fig. 1. Coordinates used in PTC distiller. The dashed line corresponds to the line focal of the parabolic cylinder ($x = 0$; $y = 0.7$ m). The dimensions of the concentrator are 2.5 m in the z coordinate, 2.2 m in the x coordinate and 0.47 m in the y one.

Fig. 2. Photographs of the three cavity configurations used in the experiment.

extreme dimension of the sheet from the middle point (vertex), taking into account sheet dimensions and its arc length $L = \left[\frac{x\sqrt{4p^2 + x^2}}{4p} + p\ln\left|\frac{x + \sqrt{4p^2 + x^2}}{2p}\right|\right]_{x_1 = 0}^{x_2 = 0.11}$.

The absorber cavity is made of a rectangular black aluminum tube of 8.2 cm × 4 cm cross section and 1m of length (this tube was selected because it is cheaper than other ones and it is easy to obtain in commercial shop). It has two transparent pieces of acrylic material of 10 cm × 10 cm × 2.5 cm covering the extremes of the cavity. One of them has an inlet pipe of sea water and the other one has a pipe to outlet vapor. There were tested three configurations, Fig. 2: (i) cavity “a” is referred to a rectangular tube, (ii) cavity “b” is the same rectangular tube with a thermal insulation only in the upper side (fixed by a glass), and (iii) cavity “c” is the same one with the thermal insulation in the upper side and lateral glasses as a wind protection (without vacuum). The bottom side is free of glass or thermal insulation in the three cases.

For thermal insulation and wind protection was used a 5 cm thick of rock wool (0.035 W/(m K) at 70°C) and 4 mm thick of transparent glass, respectively. In all configurations, the area of the bottom side of the absorber cavity was 0.082 m^2. The vapor produced in the cavity is transported through copper tubes to a heat exchanger which is cooled by 2 liters of pumped water which in turn flows through a fan cooled radiator. The pump and the fan are powered directly to a 10 W*p* PV panel (without rechargeable batteries). It is important to maintain the cavity with about 1cm height of sea water always, to avoid structural damage because high temperature. In this sense, it is used a system that controls the water level, as shown in Fig. 3. In Fig. 4 is shown the PTC solar distiller used in experiments.

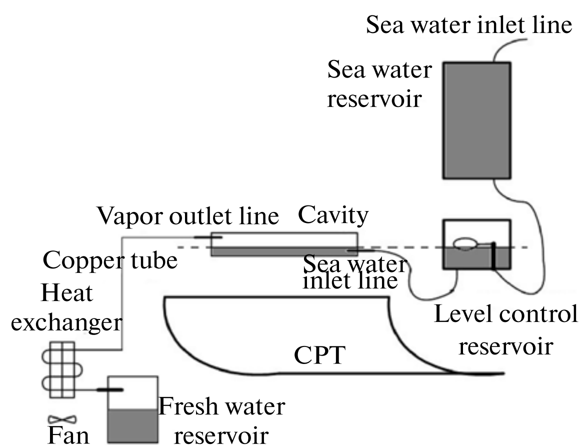

Fig. 3. Schematic diagram of PTC distiller. The dashed line indicates the water level inside the cavity. The gray shadow represents water in the system.

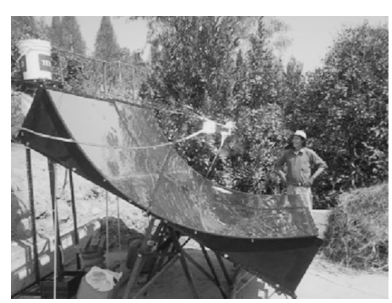

Fig. 4. Photograph of the PTC distiller installed in Cocayalta (Lima, Peru).

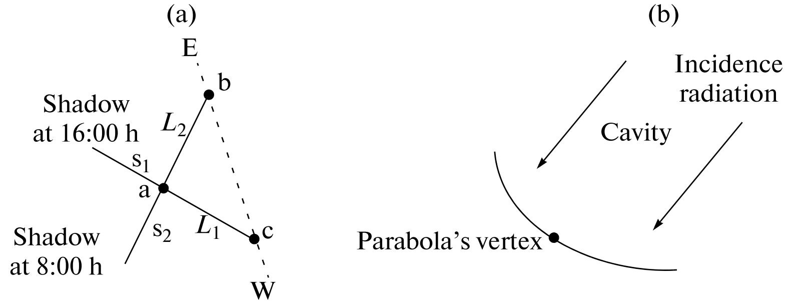

Fig. 5. (a) The dashed line is the East–West direction, obtained from sunlight's shadows (s_1 and s_2). (b) The angle of the PTC respect to the horizontal plane is obtained by rotating it until the shadow of the cavity is over the vertex of the parabola.

ALIGNMENT OF THE PTC

The PTC has no solar tracking system, therefore it is firstly oriented to the East–West direction and then it must be rotated until obtain a perpendicular solar incidence (Fig. 5b). This process must be made only one time a day. To obtain the East–West direction it is taken the shadow of sunlight at 16:00 h a day before the test and the other one at 8:00 h the same day of the experiment (s_1 and s_2 from point "a" in Fig. 5a). Then there are traced the L_1 and L_2 lines, where $L_1 = L_2$ to obtain the points "b" and "c". The line across these points is the desired direction.

EXPERIMENTAL TESTS

The PTC distiller was tested in Cocayalta (48 km from Lima, 930 m above sea level, latitude 11°33′44.1″, longitude 76°43′21.3″, at river Chillon valley) only during this period of test operation. The ambient temperature was measured with a BOECO thermometer (–20°C to +250°C) in a shadow side, the cavity temperature was measured in its bottom side by using a RAYTEK Minitemp pyrometer and a hand-made radiometer was used to measure the radiant flux of incident solar radiation, disposed over the x–z plane (Fig. 1).

Tests were performed to compare the fresh water production using the same PTC reflector and hydraulic system but only changing the three cavities described before. In this sense, it was measured the radiant flux (W/m^2), ambient and cavity temperature (°C), and fresh water volume (mL). Results are shown in Fig. 6. The left ones correspond to the PTC using the cavity "a" (on August 14th 2011), the middle ones using cavity "b" (on September 4th 2011) and the right ones using cavity "c" (on October 22th 2011).

DATA ANALYSIS

Although tests were made in different days, it is possible to compare the total solar radiation energy and the fresh water volume obtained for each case. Results are presented in Table 1.

From this table it is observed an important increase between the fresh water production of cavities "a", "b" and "c" although the total solar energy was different in the days when they were tested. For example, there is a 69.2% increase in water production versus 17.7% increase in solar energy (on August 14th 2011 and September 4th 2011, respectively) when comparing the results of the "a" and "b" cavities. In the same way, when comparing "a" and "c" cavities, there is a 95.7% increase in water production versus 23.3% increase in solar energy (on August 14th 2011 and October 22th 2011, respectively). It was expected that water production is directly proportional to solar energy, but these results are different. Then, this difference could be explained by the heat loss in each cavity, which is reduced drastically from cavity "a" to cavity "c" by the use of the thermal insulation and lateral wind protection, as shown in Fig. 7.

Finally, the fresh water obtained was analyzed and compared with the sea water used in the tests. Results obtained are shown in Table 2. As it can be seen, the fresh water must be chemically treated to be drunk.

Table 1. Solar energy and fresh water volume obtained for each cavity configuration

Cavity	Solar energy MJ/(m^2 day, kW h/(m^2 day)	Fresh water volume cm^3/day, L/day
a	13.61 (3.78)	3250 (3.25)
b	16.02 (4.45)	5500 (5.50)
c	16.78 (4.66)	6360 (6.36)

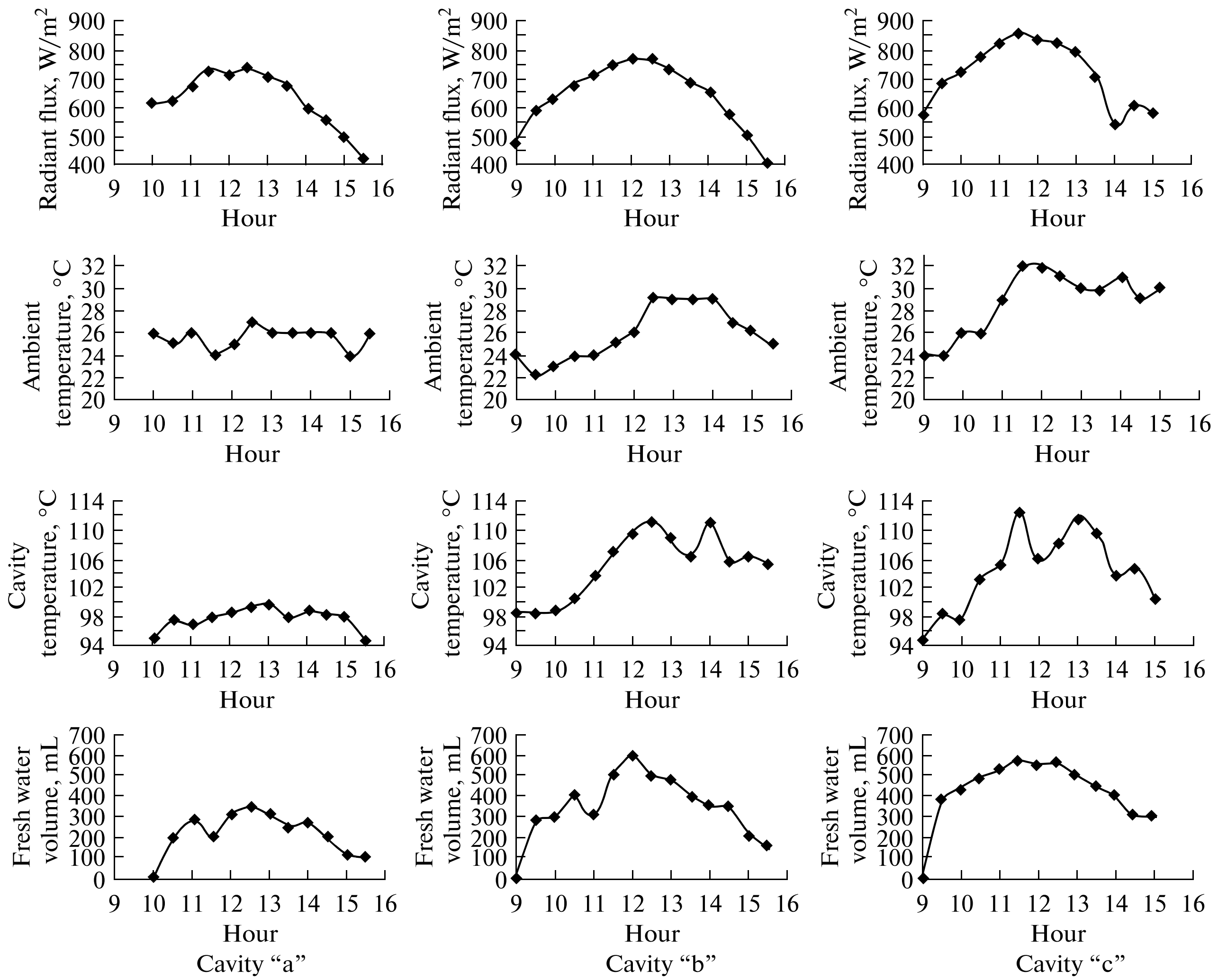

Fig. 6. Graphics of radiant flux, ambient temperature, cavity temperature and fresh water volume versus hour, using cavity "a" (left ones), cavity "b" (middle ones) and cavity "c" (right ones). The scales are similar in the three cases for comparison.

DISCUSSION

There are some experimental considerations to obtain a good operation of this kind of distiller. First, the solar radiation must be reflected over all the length of the cavity all day long. Otherwise, the cavity cools very rapidly and the vapor production stops. For this reason the length of the PTC (along z coordinate in Fig. 1) is larger than the cavity one (2.5 m and 1 m, respectively), both of them aligned in the East–West

Table 2. Parameters obtained for fresh and sea water used during the testes. Also are shown the Peruvian parameters for human drinking water [8]

Parameter	Sea water	Fresh water	Peruvian law	Units
Chloride	16129	17	250	mg/L
Conductivity	54000	22	1500	μS/cm
Carbonated hardness	6360	3	500	mg/L
Oxygen dissolved	4.6	5.00	>=6	mg/L
pH	7.99	6.30	6.5–8.5	pH
Salinity	3.4	0.00	–	%
Total dissolved solids, TDS	26800	12	1000	mg/L
Turbidity	16.4	0.20	5	NTU
Biochemical oxygen demand	9.9	2.40	3	mg/L

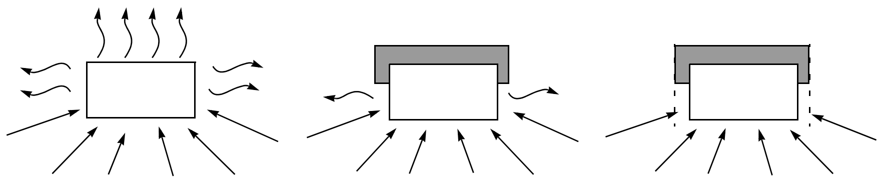

Fig. 7. Cross section of the three cavities used in tests. Arrows represent solar radiation reflected from PTC to the cavity. Curved lines represent the heat loss by the cavity. The gray shadow represents the thermal insulation and dashed lines are the lateral glass protection.

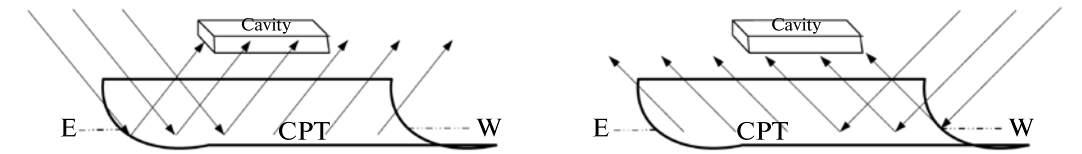

Fig. 8. Representation of solar radiation incidence from 8:00 h (left) to 16:00 h (right). The cavity must be completely inside the radiation reflected by PTC all day long.

direction. The size of the PTC was selected due to the available area to do experiments and the length of the cavity was calculated using the following viewpoint: for the azimuthal angle of solar radiation at 8:00 h and 16:00 h, it was calculated that a distance of 0.75 m from each extreme of the PTC is sufficient to maintain all the length of the cavity inside the area of the solar radiation reflected, as shown in Fig. 8. As a consequence, fresh water production is about 6.36 L/5.5 m^2 = 1.16 L/m^2. However, if the length of the cavity is increased into 10 m, it is sufficient 11.5 m of PTC's length, so fresh water production increases to 2.51 L/m^2. Second, it is important to take into account that the distiller was tested in a region with no much intense solar radiation, 16.78 MJ/(m^2 day) (4.66 kW h/(m^2 day)), therefore its production is low, but it could increase if it operates in regions with higher incidence of solar energy. The last consideration is also important when considering the cost production of fresh water.

The PTC distiller was made by reusing wood and metal to construct the structures that support the reflector surface (aluminum sheets), cavity and reservoirs. Tubes were reused to construct pipelines and heat exchanger. It was bought only two aluminum sheets, the cavity tube, the DC fan, the DC pump and the rock wool, with an investment of no more than US $ 150.00. Even more, recently it was tested a heat exchanger that needs no solar fan or pump, so these two components are no important to investment calculations.

In this work, it was no investigated about what to do with the brine obtained during the process of desalination, but it is important no mention that if the brine is removed from the cavity when it is still warm at end of operation (about 17:00 h), the cavity material is hardly affected by residual brine. Remember that there is no salt layer because the cavity has always a 1 cm of sea water level.

Finally, there is a huge loss of thermal energy when the vapor is condensed inside copper tubes, by cooling them externally in the heat exchanger. However, it is possible to use these tubes as heaters for another solar distiller, for example a step wise model [5], to obtain more production than the PTC and the step wise when each one operates separately.

CONCLUSIONS

It was tested a simple and low cost PTC distiller without solar tracking system, but aligned in the East–West direction, therefore it only must be positioned one time a day. It is possible to double the fresh water production using a simple thermal insulation and wind protection in the cavity absorber. Because of its little dimensions and a poor solar energy (see Table 1), it was obtained a production of 1.16 L/m^2. However, production could be increased to 2.51 L/m^2 (about 116%) if the cavity length is increased in 10 times (with the same solar intensity), because the length of the PTC must be increased only in 4.6 times. In spite of its low fresh water production, this device has a very low cost because almost all materials used in its construction are reused ones (except the aluminum sheet and the tube used to made the cavity) and it is not necessary a solar tracking system. It was observed during tests that if the brine is removed being still warm, the material of the cavity is hardly affected. Finally, it was verified that parameter values of fresh water obtained indicate that could be used for human consumption with a previous chemical treatment.

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