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SOLAR POWER PLANTS AND THEIR APPLICATION

Design and Construction of a Fresnel Linear Distiller[1]

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Abstract—It was designed a Fresnel linear distiller based on optical calculations obtained from taking into account Lima's latitude value, Earth inclination angle and heat absorber cavity's dimensions. The 5.6 m^2 reflective surface concentrator of the distiller was constructed with 32 plane rectangular mirrors; the heat absorber cavity was made with a rectangular blackened aluminum tube 1 m long and installed 2.5 m over the plane of mirrors. The Fresnel linear distiller was installed at the University of Lima and experimental tests were performed during no cloudy summer days. There were measured ambient temperature, heat absorber cavity temperature, radiant flux and fresh water volume. From this, it was obtained a production of 0.89 liters/hour and 0.79 L/m^2, and it was calculated a total performance of 34.5% in desalting sea water. Finally, it is presented a comparison between Fresnel linear distiller (FLD) and parabolic trough distiller (PTD) with similar dimensions and characteristics. It is obtained that the last one produced almost 32% more fresh water than the former, but at the same time, the FLD is almost 20% cheaper than PTD. However, water cost production with both distillers using is almost the same.

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INTRODUCTION

A Fresnel Linear Concentrator (FLC) [1] presents several economic advantages when it is compared to a Parabolic Trough Concentrator (PTC) in solar power plants. In fact, it was demonstrated that a solar power plant costs 55% less by FLC's using than by PTC's using in spite of it covers a 36% higher area than a PTC one, to produce the same power [2]. There are three main differences: first, manufacturing reflective surfaces with a parabolic geometry is more expensive than manufacturing flat ones; second, parabolic surfaces must be supported by large mobile structures unlike those required by flat surfaces; third, the CFL heat absorber cavity is kept fixed, while in the PTC it must be mobile, therefore, there is greater pressure loss [3].

It is important to take into account optical and thermal annual efficiency to generate electricity in a solar power plant. Using a PTC these values are about 58 and 85%, respectively. In the FLC case, they are 43 and 76%, respectively. It was calculated a global efficiency of about 15% in a PTC power plant and about 9.3% in a FLC one [2]. The optical efficiency is less in a FLC than in a PTC one due to orientation of the reflective surface with respect to sunlight [4], as can be seen in Fig. 1. For this reason, some modifications are being investigated to improve optical efficiency as the use of curved surfaces (spherical or parabolic) instead of flat ones [5].

[1] The article is published in the original.

DESIGN OF THE FRESNEL LINEAR DISTILLER

Although solar incidence over flat mirrors is not perpendicular in the FLC, it is possible to minimize losses in optical efficiency considering the following criteria: (i) the size of the mirrors must be such that the reflected solar radiation does not exceed the size of the absorber cavity (scatter effect); (ii) the reflected radiation must not be obstructed for the adjacent mirror dueto an insufficient spacing (effect of overlap). But if the spacing is greater, results in an increase of the area that must be covered with mirrors and, as demonstrated below, the size of each mirror should decrease considerably, increasing their number.

Taking into account that the FLC will be oriented in West–East direction, the solar incidence angle α (Fig. 2) is constant during all day long and depends on Lima's latitude (φ ≈ –12°) and the Earth's inclination

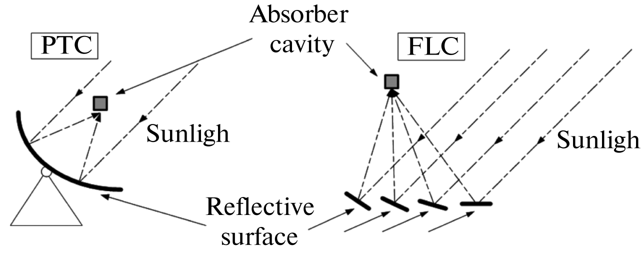

Fig. 1. Schematic diagram of a PTC (left) and FLC (right) with respect to sunlight.

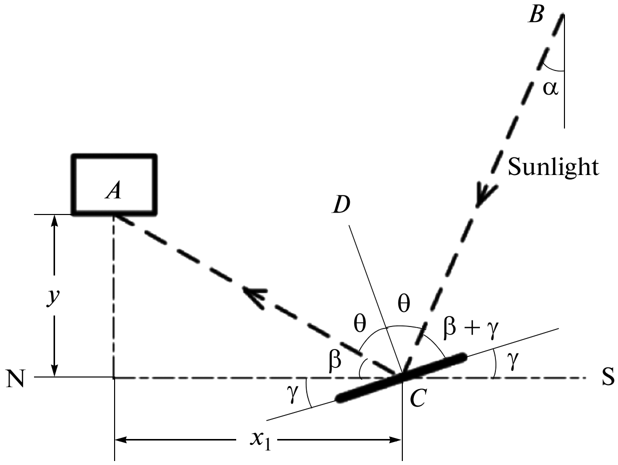

Fig. 2. Diagram of the cavity (solid rectangle in *A*) and the cross-section of one mirror (thick solid line in *C*). The discontinuous line *BCA* represents sunlight trajectory, *CD* line is perpendicular to the mirror and *y* is the height of the cavity from the mirror's plane.

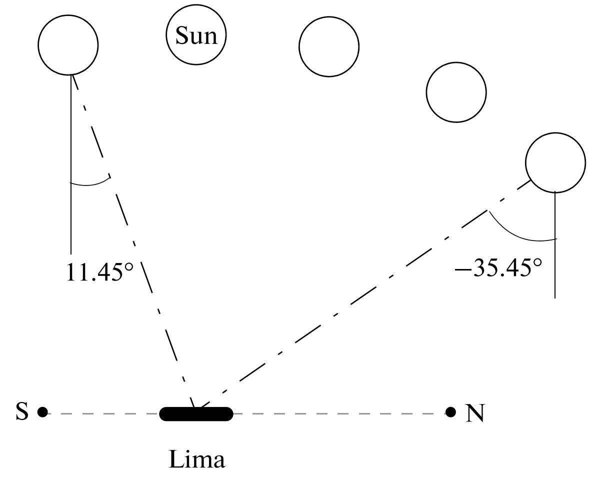

Fig. 3. Sun position for an observer in Lima during a year (the East-West direction is perpendicular to the sheet). In June 21th the sunlight's incident angle is 35.45° to the north of Lima. In December 21th this angle is 11.45° to the south of Lima.

angle ($-23.5° < \delta < +23.5°$). Thus, α is calculated by $\alpha = \delta + \varphi$, whose values vary between $-35.45°$ (north from Lima) and $+11.45°$ (south from Lima) throughout the year, as it is shown in Fig. 3.

Based on Fig. 2, the inclination angle of each mirror respect to the horizontal plane (γ), is calculated by

$$\gamma = \frac{90° - \beta + \alpha}{2}, \qquad (1)$$

where β is an angle that depends exclusively on the distance x_1 and the height y between the cavity and the mirror's plane, $\beta = \arctan(y/x')$.

A positive/negative value of γ corresponds to counterclockwise/clockwise rotation of the mirror respect to the horizontal plane. By the "scatter effect" (Fig. 4) it is possible to estimate the width (L) of each mirror such that width of the sunlight reflected (x') be always less than the width of the bottom side of the cavity (0.08 m) for each value of α throughout the year. The equation for calculating the scattered radiation x' is

$$x' = L\frac{\mathrm{Sen}\left[45° + \left(\frac{\beta - \alpha}{2}\right)\right]}{\mathrm{Sen}(\beta)}. \qquad (2)$$

It is possible to define an optical performance (η_0) as the loss of energy because the scatter effect by

$$\eta_0 = \frac{h'}{x'}(100\%). \qquad (3)$$

By Fig. 4 using, the Eq. (3) results in

$$\eta_0 = 100\mathrm{Sen}(\beta). \qquad (4)$$

Therefore, the optical performance only depends on the height and distance between cavity and each mirror. As a consequence, it is better to place the cavity as higher as possible and decrease the distance of mirrors as less as possible. As can be seen in Fig. 5, the mirror just below the cavity ($x' = 0$) has $\eta_0 = 100\%$, but the mirror at $x' = 1.5$ m has $\eta_0 = 55\%$ if the cavity is at $y = 1$ m and 85% at $y = 2.5$ m.

Also, it is also important to take into account the overlap effect to prevent reflected sunlight is not hindered by the adjacent mirror, as it is shown in Fig. 6.

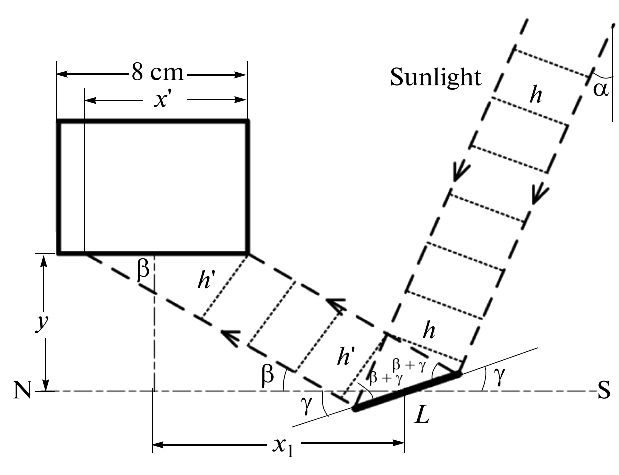

Fig. 4. Schematic of sunlight scattered over the bottom side of the cavity (0.08 m, solid rectangle) by one flat mirror with *L* width (solid line).

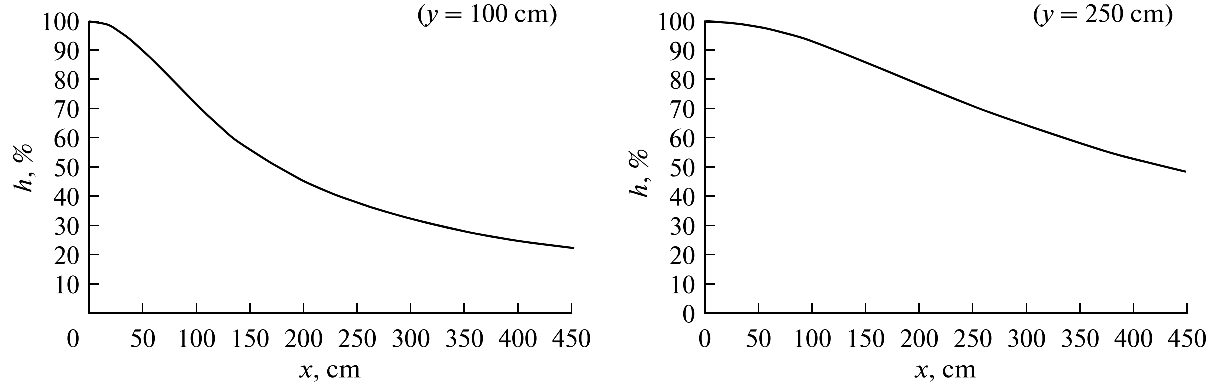

Fig. 5. Optical performance (η_0) versus distance from the cavity (x' in Fig. 4) for $y = 1$ m and $y = 2.5$ m.

For every α value at Lima, φ must be less than β_2. Thus, it is possible to calculate the minimum separation $d = x_2 - x_1$ between adjacent mirrors by the following equation:

$$\phi = \arctan\left[\frac{L(\mathrm{Sen}(\gamma_1) + \mathrm{Sen}(\gamma_2))}{L(\cos(\gamma_1) + \cos(\gamma_2)) - 2d}\right]. \quad (5)$$

Finally, taking into account Eqs. (1), (2), (5) and $-35.45° < \alpha < +11.45°$, it was determined that the best values for the concentrator are $L = 0.07$ m for a mirror's width and $d = 0.08$ m for minimal distance between adjacent mirrors when $y = 2.5$ m for the height of the cavity. Also, the length of each mirror was 2.5 m then it was necessary an array composed of 32 mirrors to cover an area of 5.6 m^2 (the last value was chosen to compare with results obtained previously using a parabolic trough concentrator [6]). Figure 7 shows the final design of the Fresnel linear distiller. Thus, by Eq. (4) using with $0 < x_1 < 1.3$ m and $y = 2.5$ m, the optical performance of the Fresnel linear concentrator is about 95%.

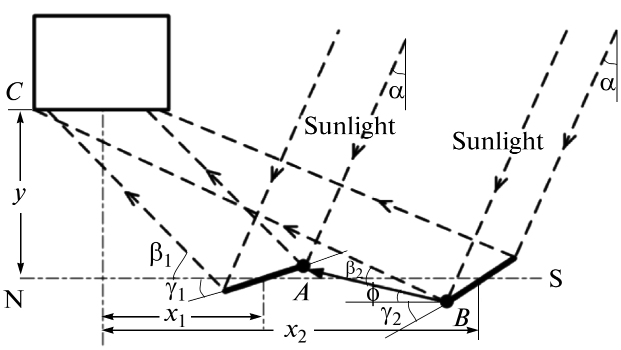

Fig. 6. Schematic of sunlight reflected by two adjacent mirrors (thick solid lines) placed at x_1 and x_2, respectively.

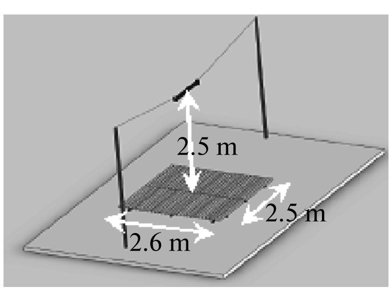

Fig. 7. Fresnel linear distiller design.

DESCRIPTION OF THE DEVICE

The device has an array of 32 mirrors (2.5 m long, 0.07 m width and 0.04 m thick each one) supported by a wooden structure. Each mirror is held by three hinges (made of wood, clamps and water pipes) to allow them to rotate. The cavity is made of a rectangular black aluminum tube (0.082×0.04 m cross section and 1m of length), with an inlet of sea water and an outlet of steam. Also, it has thermal insulation in its upper and lateral sides (0.05 m thick of rock wool) and lateral glasses as a wind protection, only the bottom side is free of glass and thermal insulation. This cavity is fixed 2.5 m height from mirrors by a metallic structure. The steam produced in the cavity is transported through a copper tube (diameter = 0.0012 m) to a heat exchanger. The whole system is shown in Fig. 8.

A day before experimental tests, cavity and mirrors must be aligned to the East–West direction. This is obtained by drawing on the floor two points at a distance of 1 m from a point of reference: one of them over the shadow direction of sunlight at 9:00 h and the other one at 15:00 h; the line across these points is the desired direction. Also, mirrors must be cleaned. The operation of the device begins after all mirrors are rotated until sunlight is reflected over the bottom side of the cavity. The 0.8 liters of sea water inside the cavity begins to boil about 8 minutes later. It is important to maintain the cavity with about 1 cm height of sea water, to avoid structural damage (because if it has no

Fig. 8. Photographs of Fresnel linear distiller installed at University of Lima (Lima, Peru).White arrow indicates the heat absorber cavity in which boils seawater. Seawater inlet is on the right side of the cavity, steam outlet is on its left side and it is connected to a heat exchanger (tube in spiral shape).

water it achieves high temperatures quickly). After operation, brine must be removed from the cavity when it is still warm (around 17:00 h) because in this condition aluminum is hardly affected. It was verified that cavity should be replaced every 3 or 4 months but if brine is removed the next day of operation cavity should be replaced every 2 or 3 weeks. Salt obtained from brine is being investigated as a heat absorber material to maintain high temperatures during night inside heat-pipe evacuated-tube solar collectors.

EXPERIMENTAL TESTS

Experimental tests were performed at the University of Lima (latitude –12.08°, longitude –76.97° and 207 m above sea level) in several days of similar climate characteristics during Lima's summer. In Fig. 9 experimental results are shown, that obtained on January 26th and April 6th 2013, for example. The ambient temperature was measured with a BOECO thermometer (–20° to +250°C), the bottom side cavity temperature was measured by a Raytek Minitemp IR thermometer using and aportable TENMARS TM-206 radiometer was used to measure the radiant flux of incident solar radiation perpendicular to the horizontal plane.

DATA ANALYSIS

The total performance (η) of the Fresnel linear distiller should be calculated by comparing the experimental fresh water volume obtained (V_{ex}) respect to the theoretical one (V_{th}), as it is shown in Eq. (6):

$$\eta = \frac{V_{ex}}{V_{th}} x \times (100\%). \quad (6)$$

It is necessary 2.62 MJ of energy to convert 1 L of sea water in steam by boiling, therefore the theoretical value V_{th} was calculated by:

$$V_{th} = \frac{E_{total}[MJ]}{2.62}[l]. \quad (7)$$

In this equation, $E_{total} = ExA$ and $E = Pxt$, P (radiant flux) and t (time) are shown in Fig. 9, by using of the data between 10:00 and 15:00 h. The area A is calculated by $32 \times 0.07 \times 1$ m = 2.24 m^2. In this last calculation, it was used only the area corresponding to the 1 m length of mirror that reflects sunlight over the cavity (Fig. 10). Results are presented in Table 1.

As can be observed in Table 1, there is a difference of 13.8% in total performance between these two days. This difference could be explained because experimental data of radiant flux was taken each 30 min, therefore total energy in Eq. (7) is affected.

Moreover, it is interesting to compare two similar distillers the only difference between them is the geometry of reflective surfaces. In previous investigation [6], it was used a parabolic-trough concentrator as a distiller that operated using the same materials and dimensions in the heat absorber cavity as well as copper tube spiral shape as a heat exchanger that were used in the Fresnel one. Both of them, Fresnel linear distiller (FLD) and parabolic-trough distiller (PTD) have a reflective surface area of 5.6 and 5.5 m^2, respectively, and must be oriented in the West–East direction for achieve its optimal operation regime. The reflective surface of the FLD is glass mirror 4 mm and the PTD one were two aluminum sheets 0.4 mm thick.

For comparison, in Table 2 there are presented the values obtained only between 10:00 and 15:00 h, on January 26th 2013 (in Lima) corresponding to FLD and October 22th 2011 to PTD (in Cocayalta, 40 km

Table 1. Solar energy, fresh water volume and total performance (Eq. (6)) obtained in Fresnel linear distiller in two days climatically similar and between 10:00 and 15:00 h

Date	E, MJ/m^2 day	E_{total}, MJ/day	V_{ex}, mL/day	η, %
Jan 26th 2013	13.88	31.09	4090	34.47
Apr 6th 2013	13.90	31.14	3530	29.71

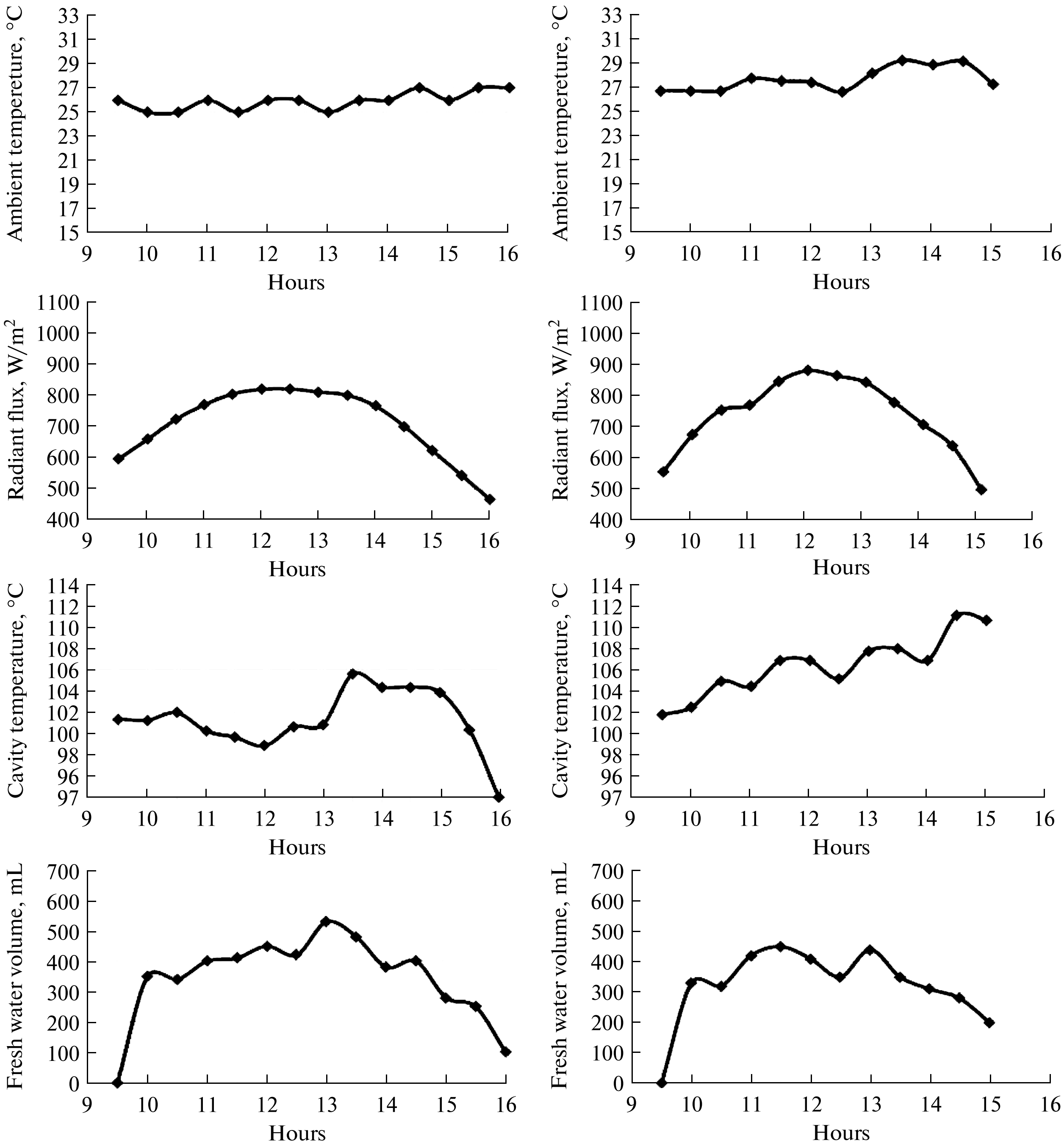

Fig. 9. Graphics of radiant flux, ambient temperature, cavity temperature and fresh water volume versus hour, obtained on January 26th 2013 (left ones, total fresh water obtained in 6.5 hours: 4790 mL, solar incidence angle $\alpha = 8.9°$) and on April 6th 2013 (right ones, fresh water in 5.5 hours: 3860 mL, $\alpha = 18.3°$). The scales are similar for comparison.

away from Lima). From these results, it was obtained that the FLD produced 0.89 L/h of fresh water while PTD 1.01 L/h. In the same way, FLD produced 0.79 L/m^2 while PTD 0.92 L/m^2. Another result is about characteristics of fresh water obtained in FLD. It was verified that presents the same values obtained by PTD using due to process and materials are the same.

In fact, from FLD it was obtained a conductivity of 16 from 17000 mg/L of seawater, pH = 6.25 from 8, salinity 0 from 3.4% and turbidity 0.21 NTU from 16.5 NTU of sea water. Unfortunately, in these distillers is not possible to evaluate salinity of fresh water as a function of the temperature of evaporation, because it is obtained from steam (~100°C) condensed in heat exchanger.

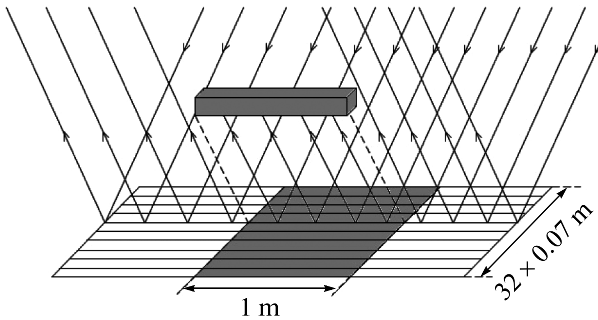

Fig. 10. Gray shadow shows the 2.24 m^2 of mirrors that reflect sunlight over the cavity. This shadow moves during all day long.

At the less temperature, for example between 70 to <100°C, when sea water is not still boiling, its evaporation is hardly collected and condensed in the heat exchanger. It is possible that it condensates inside the cavity. Finalizing the comparison, materials used for distillers were reused but it should be supposed that all materials were bought for the construction of both distillers, therefore FLD results 19.6% cheaper than PTD. Thus, if it is supposed 300 days with sunshine 1 year, 10 m long of reflective surface (instead of the current 2.5 m) and a heat absorber cavity 8.5 m long, the cost of each liter produced by PTD is US $0.24 and US $0.23 by FLD using (in this case it was considered only manufacturing cost without maintenance and operation).

Table 2. FLD and PTD experimental results obtained in two days climatically similar and between 10:00 and 15:00 h

Device	E, MJ/m^2 day	E_{total}, MJ/day	V_{ex}, mL/day	η, %
FLD	13.88	31.09	4090	34.47
PTD	13.18	29.00	5070	45.82

CONCLUSIONS

It is demonstrated that Fresnel linear concentrators aligned in the East–West direction could be used for sea water desalination, using only solar energy because it does not require a solar tracking system. In a clear day for example, during 6.5 hours of operation, the Fresnel lineal distiller (constructed with an array of 32 mirrors, 5.6 m^2 and heat absorber cavity 1 m long) received 31.09 MJ of solar energy and the distiller produced 4.8 liters of fresh water. Taking a mean value obtained on several days climatically similar FLD achieve a total performance of 32%.

In addition, it was compared a Fresnel linear and a parabolic-trough distiller (FLD and PTD, respectively) of similar characteristics except the reflective surface geometry. It was obtained that PTD produces 32.9% more fresh water than FLD but the last one is 19.6% cheaper. The cost of fresh water production is practically the same with both distillers.

REFERENCES

1. Mathur, S.S., Kandpal, T.C., and Negi, B.S., *Energy Convers. Manag.*, 1991, vol. 31, no. 3, pp. 205–219.
2. Morin, G., Dersch, J., Platzer, W., Eck, M., and Haberle, A., *Solar Energy*, 2012, vol. 86, pp. 1–12.
3. Velázquez, N., García-Valladares, O., Sauceda, D., and Beltrán, R., *Energy Convers. Manag.*, 2010, vol. 51, pp. 434–445.
4. Najla El Gharbi, Halima Derbal, Sofiane Bouaichaoui, and Noureddine, S., *Energy Proc.*, 2011, vol. 6, pp. 565–572.
5. Abbas, R., Montes, M.J., Piera, M., and Martinez-Val, J.M., *Energy Convers. Manag.*, 2012, vol. 54, pp. 133–144.
6. Saettone, E., *Appl. Solar Energy*, 2012, vol. 48, no. 4, pp. 254–259.