

DOUBLE SLOPE SOLAR STILL WITH IMMERSSED FINS: THEORETICAL AND EXPERIMENTAL STUDY

H. MOUNGAR¹, A. AZZI², Y. SAHLI³, A. HIEDA⁴

This work presents a theoretical and experimental study of a double slope still with immersed fins. The influences of the distance between fins, fin heights, fin numbers and water layer thickness on the solar still production are investigated. From the obtained results, the distance between fins has no significant effect on the still productivity. Moreover, for fin heights from 2 to 5 cm, a still productivity raising is caused, when the fin heights are from 6 to 8 cm an increasing in the still production is found. A larger fin numbers lead to a rising in the produced water amount. The water quantity augmentation in the basin makes the water productivity decreasing. The experimentally obtained results during the day June 11, 2016, show that the solar still with immersed fins productivity was about 15 to 27 % higher than that of the simple solar still, under the following conditions, i.e. $mw = 42.61 \text{ kg}$, $h1 = 3.6 \text{ cm}$, $Vw = 3.5 \text{ m/s}$, $lw = 5 \text{ cm}$ and $Nfins = 12$.

Keywords: Solar Still, Distilled Water, shadow, immersed fins, Radiative flux

1. Introduction

Fresh water represents only 3% from the total amount of water available on earth. Only 1 % of this quantity is usable, the rest is in the glace form or buried underground. Arid regions are characterized by droughts; they are poor in superficial water, which is generally saline. This is the case of some regions in southern Algeria, namely Bouda, Abadla, etc. Using the solar desalination process could offer economic and environmental benefits for the drinking water supply system in these regions. Several research works have investigated, experimentally and theoretically, the parameters influencing the productivity of different configurations of a solar still.

D. Bechki (2010) studied the effect of shadow of an intermittent partial coverage on the efficiency of a single basin double slope solar still. The daily production in the first series was found equal to 6.01 (l/m²/day). This quantity

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was improved by 33.7% in the second series. The third one consisted of reducing the temperature of the transparent cover by means of shadows of the intermittent glass cover on the north side. This procedure allowed an additional 12% improvement in the daily production of distillate. (A. K. A.E. Kabeel 2012) Conducted an experimental and theoretical study on two types of solar stills, namely a conventional inclined solar still and a cascade solar still, which were tested simultaneously. They also examined the influence of the depth and width of the tank on the performance of the solar still. The cascade solar still was supplied with hot water coming from an evacuated tube solar collector. To increase the heat exchange surface, they used a wick on the vertical sides of the cascade distiller. In this case, the daily efficiencies, for one liter of distillate, for the cascade and conventional solar distillers were found to be approximately 53 and 33.5%, respectively. (H. Al-Hinai September 2002) Developed a mathematical model to predict the productivity of a simple solar still, under different climatic conditions in Oman. They found that the optimum design is obtained for a glazing with an inclination angle of 23°, and an insulation thickness equal to 0.1 m. With such a design, the distiller can produce 4.15 kg/m² of water per day. Next, they improved their model based on a technical and economic study; they found that the unit cost for distilled water obtained from the solar still was \$ 74/1000 gal. (C. E. Okeke 1990) Studied the effects of coal and charcoal on the performance of a solar still designed and manufactured with local and sustainable materials that are available on the market. Both kinds of coal can improve the performance of the distiller, as well as its daily productivity and efficiency, with an average of 1.12 l/m² and 16.5%, respectively. (P. Cooper 1969) Developed a method for calculating the effective fraction of solar radiation incident on the still surface. The variables that influence the operation of the distiller are the day of the year, latitude, inclination angle of glazing, orientation of the distiller, fraction of the scattered radiation and solar radiation on the system. He discovered that the intermittent sunshine has a negligible effect on performance, and also the increase in the percent of daily diffuse radiation decreases absorption. (Hassan E.S. Fath 2002) Conducted a theoretical study on a single basin double slope solar still. The first cover glass, transparent and oriented towards the south, acts as an evaporator; the second one is tinted and oriented towards the north, and acts as a condenser. They added a black dye into the basin of the distiller in order to improve the absorption of the plate and to increase the evaporation surface. Then, they studied the influence of climate and geometric parameters on the productivity of the distiller. They also carried out frequent instantaneous cooling of the transparent cover, for example every hour. The efficiency was improved by 55% compared to that of a single basin still. (K. Voropoulos, 2004) Studied a hybrid solar desalination system consisting of a conventional solar still coupled to a field of solar collectors and a storage tank for hot water. Distilled water production of a

coupled system is much higher than that of a non-coupled distiller. In addition, this system has the advantage of providing hot water from its storage tank. The experimental results obtained in the laboratory were found to be consistent with theory, with an accuracy of about $\pm 3\%$. The experimental results show that a draft of hot water with a volume equal to 1/4, 1/2 or 1 volume of the storage tank reduces the production of distilled water by 36, 57 or 75 %, respectively, with a simultaneous energy output of about 1900, 3300 and 5200 MJ. (Eduardo Rubio 2004) Conducted a theoretical study on the parameters that may have an impact on the production of distilled water in a double slope solar still. The maximum production of distilled water through the two transparent covers, oriented east and west, is 0.19 and 0.18 [kg/m²/h], respectively. (Imad Al-Hayek a 2004) Studied two types of solar stills, one is simple with a vertical mirror, and the other is a double slope solar still. They found that the productivity of the distiller with a vertical mirror is 20 % greater than that of the double slope still. The temperature of water surface is closely related to the incident solar radiation. Decreasing the thickness of the water layer and adding the dye increase the amount of distilled water produced. (Z. O. A.E. Kabeel 2014) Proposed to add an external condenser to the distiller and to use Nano fluids in order to increase the productivity of distilled water by 53.2 and 116%, respectively. (M. Mustapha Belhadj 2015) Suggested attaching a condensation cell to a double slope distiller in order to improve the productivity of the system by about 60 %, which is higher than that of a conventional distiller or a solar distiller with capillary film. (M.M.Morad 2015) Proposed the periodic cooling of the glazing cover of the distiller. (Benhammou M June 2014) Studied the shadow effect of the reflector on the productivity of the distiller (Rahul Dev 2011) (Tanaka and Nakatake 2006) (A.A El-Sebaii 2015) Investigated the effect of height, thickness and number of fins on the production of an ordinary distiller; this caused the production of distilled water to increase by 13.7 %, compared to a simple distiller. A theoretical and experimental study of a double slope solar still, with fins immersed in the basin, is conducted in the present work, while taking into account the shading effect of vertical surfaces on the productivity of distilled water.

2. Theoretical study

The mathematical model that describes the solar still operation is based on the thermal balance equations in each distiller element. Fig.1.

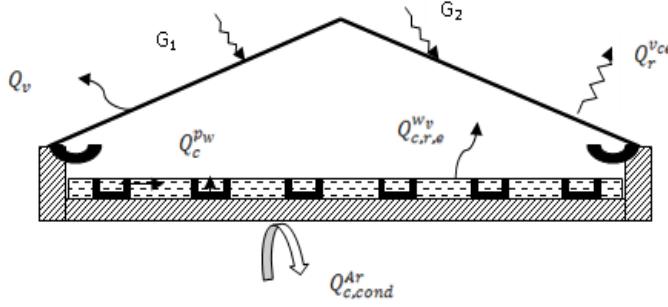


Fig. 1: Distillation heat balance.

The heat balance equation in the solar still transparent cover is given by the following equation:

$$m_v C p_v \frac{dT_v}{dt} = (1 - \tau_v)(G_1 + G_2) + (h_c^{W-v} + h_e^W + h_r^{W-v})(T_w - T_v) - h_r^{vc}(T_v - T_c) - h_v(T_v - T_a) \quad (1)$$

The thermal balance equation in water is expressed by the following equation:

$$m_w C p_w \frac{dT_w}{dt} = \tau_v \alpha_w \left((G_1 + G_2) \frac{A_{eff}}{A_p} + G_3 \frac{A_{fin}}{A_p} \right) + h_c^{p_w}(T_w - T_v) - (h_c^{W_v} + h_e^W + h_r^{W_v})(T_w - T_v) \quad (2)$$

In the absorption plate, the balance equation is given by the following equation:

$$m_p C p_p \frac{dT_p}{dt} = \tau_v (1 - \alpha_w) \alpha_p \left((G_1 + G_2) \frac{A_{eff}}{A_p} + G_3 \frac{A_{fin}}{A_p} \right) - h_c^{p_w}(T_w - T_v) - \frac{\lambda_p}{\epsilon_p} (T_p - T_{is}) \quad (3)$$

Where $A_{fin} = 2 \cdot N_{fins} \cdot H \cdot l$ and $A_p = l_w \cdot l$

Effective area calculation depends on the rectangular vertical fin shaded area determination (Fig.2).

The effective area calculation depends on the flat plate area minus the trapeze shaded area

$$S_{\text{Shaded}} = \ell \times N \quad (4)$$

Where

S_{Shaded} : is the trapeze area, l : is basin width and N : is the normal distance between fin surface.

Shaded area it can determined by the following geometrical equation.

$$N = \frac{H \cos(\gamma_s - \gamma_p)}{\tan h} \quad (5)$$

By replacing N in Equation 4, the shaded area is written as follows:

$$S_{\text{Shaded}} = \frac{H}{\tan h} \times \ell \times \cos(\gamma_s - \gamma_p) \quad (6)$$

$$S_{\text{Shaded}} = S_f \times \frac{\cos(\gamma_s - \gamma_p)}{\tan h} \quad (7)$$

$$S_{\text{Shaded}} = \frac{s_f \cos(\gamma_p - \gamma_s)}{\tan h} \quad (8)$$

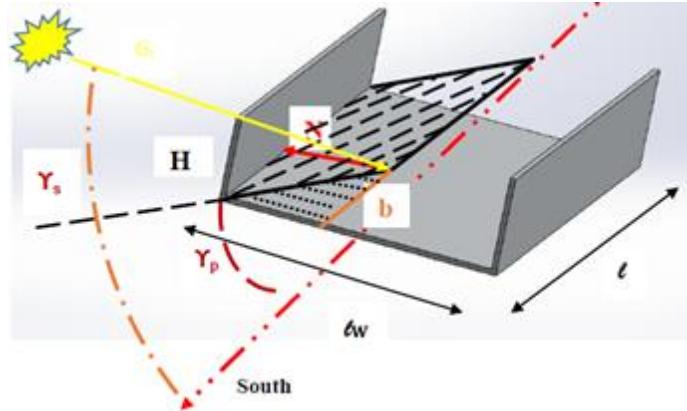


Fig. 2: Representative scheme of the shaded area.

3. Unshaded area calculation

It is the absorption plate surface that is actually reached by the incident solar radiation (effective surface).

The triangle area calculation

$$S_{\text{Not_shaded}} = \frac{1}{2} N \times b \quad (9)$$

$$S_{\text{Not_shaded}} = \frac{1}{2} \frac{H \cos(\gamma_s - \gamma_p)}{\tan h} \times \frac{H \sin(\gamma_s - \gamma_p)}{\tan h} \quad (10)$$

$$S_{\text{Not_shaded}} = \frac{1}{2} \frac{H^2}{\tan^2 h} \sin(\gamma_s - \gamma_p) \cos(\gamma_s - \gamma_p) \quad (11)$$

$$S_{\text{Not_shaded}} = \frac{1}{4} \frac{H^2 \sin 2(\gamma_s - \gamma_p)}{\tan^2 h} \quad (12)$$

The plate absorption surface is the actually not reached area by the incident solar radiation (effective surface).

$$A_{\text{eff}} = A_p - S_{\text{shaded}} + 2 S_{\text{Not_shaded}} \quad (13)$$

$$A_{\text{eff}} = \ell \times \ell_w - H \times \ell \times \frac{\cos(\gamma_s - \gamma_p)}{\tan h} + \frac{1}{2} \frac{H^2 \sin 2(\gamma_s - \gamma_p)}{\tan^2 h} \quad (14)$$

$$\frac{A_{\text{eff}}}{A_p} = 1 - \frac{S_{\text{shaded}} - S_{\text{Not_shaded}}}{A_p} \quad (15)$$

The thermal balance in the insulation:

$$m_{is} C p_{is} \frac{dT_{is}}{dt} = \frac{\lambda_p}{\epsilon_p} (T_p - T_{is}) - \left(\frac{1}{\left(\frac{1}{h_v} + \frac{\epsilon_{is}}{k_{is}} \right)} \right) (T_{is} - T_a) \quad (16)$$

Heat transfer coefficients calculation:

The heat exchange coefficient through convection between the transparent cover and the surrounding atmosphere is given by the Hottel and Woertz relation [4].

$$h_v = 5.7 + 3.8 Vw \quad (17)$$

The radiative heat transfer coefficient between the glass cover and sky is given by the following equation [4]:

$$h_r^{v-c} = \epsilon\sigma(T_v^2 + T_c^2)(T_v + T_c) \quad (18)$$

Where T_c is represented by the following equation [15]

$$T_c = T_a - 12 \quad (19)$$

The convective exchange coefficient between the absorption plate and water [reffff

$$h_c^{p-w} = (h_c^{p1-w} A_p + h_c^{p2-w} A_{fin} \eta_{fin}) \quad (20)$$

The convective exchange coefficient of the plate with brine [4]

$$h_c^{p1-w} = h_c^{p2-w} = \frac{\lambda}{l} Nu \quad (21)$$

Where Nu is the NUSSELT number, it is given by the following correlation. [4]

$$Nu = C \cdot Ra^n \quad (22)$$

The both constants are given by the Table 1. [4]

Table 1

Constants c and n			
Geometry	Ra	C	N
Vertical	10^4-10^9	0.59	1/4
	10^9-10^{13}	0.13	1/3
Horizontal	10^5-10^7	0.54	1/4
	$2.10^7-3.10^{10}$	0.14	1/3

The final efficiency is calculated by the following equation [1]:

$$\eta_{fin} = \frac{\tanh\left(\frac{z \cdot h_c^{p2w,H}}{\lambda_{fin} \cdot \theta_{fin}}\right)}{\left(\frac{z \cdot h_c^{p2w,H}}{\lambda_{fin} \cdot \theta_{fin}}\right)} \quad (23)$$

4. Results

a) Theoretical results

This study was carried out under the climatic conditions of the town of Adrar, which is located at an altitude of 264 m, with a latitude of 27.53° east and a longitude of 0.17° west. Our objective is to determine the influence of the fins

immersed in the basin on the operating performance of the distiller. The system of differential equations is solved using ODE45 under MATLAB.

Fig. 3 shows the temperatures, calculated from the theoretical model, of different components of the solar distiller, namely T_g , T_{water} , T_p and T_{ins} , which are the glass, water, plate and insulation temperatures, respectively, for the days of September 15 and January 17. It is clearly observed that these temperatures are less intense during the winter season; this is due to the solar flux which is not as strong as it is in summer or spring.

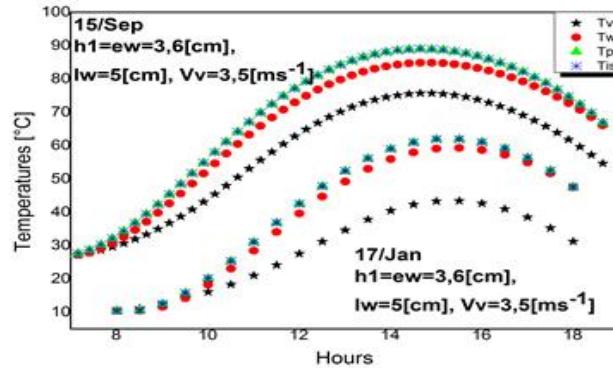


Fig. 3: Temperatures of various components in the solar distiller

Fig. 4 illustrates the daily hourly production of distilled water for the days of September 15, June 11, January 17 and March 16. It is noted that despite the high intensity of the radiative flux and high temperatures during the summer season, the production in the month June is slightly higher than that in September. Also, the distiller has a lower production during the months of January and March. High temperatures during the summer period lead to a rise in the glass-brine temperature gradient, which causes an increase in the quantity of distilled water produced.

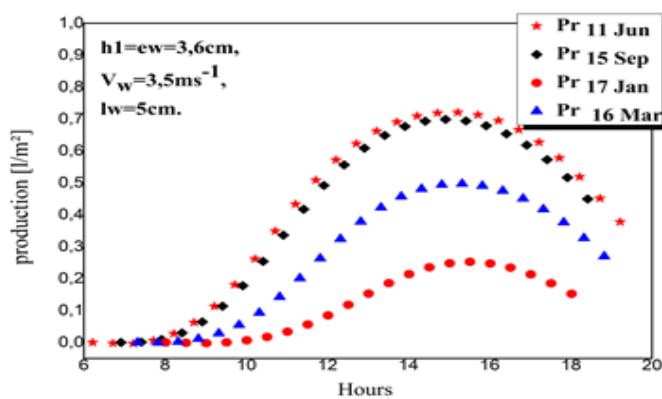


Fig. 4: Daily hourly production

b) Experimental result

Fig. 5: Experimental bench

The present work intends to present an experimental study on a solar hot-box distiller, made of a mixture of glass wool and resin to ensure good thermal insulation. Polyurethane foam, 5 cm thick, was used to reduce thermal losses from rear and side walls. This was done in order to increase the productivity of the distiller and to extend its period of operation during the diurnal period, while taking advantage of the energy stored in the basin.

The temperatures were measured using thermocouples connected to a Fluke 2680 Series data acquisition system. The radiative intensity was measured using a Kipp & Zonen pyranometer. Various series of tests were carried out during the period extending from March 04, 2015 to August 18, 2015. The temperatures, intensity of the radiative flux and quantity of distillate produced were evaluated, and a physico-chemical analysis of water was also carried out before and after the distillation. Two panes of dimensions 57 cm x 131 cm, inclined at an angle of 15 °, and a basin of dimensions 93 cm x 125 cm were also used; this gives a surface area of 1.16m². The tests were carried out on the experimental platform of the *Research Unit for Renewable Energies in the Saharan region* (URERMS), in the town of ADRAR.

Fig. 6 illustrates the evolution of ambient temperature and the intensity of the total horizontal radiative flux for the days of January 20 and July 15. It is noted that the ambient temperature follows the evolution of the solar radiation with a small offset at the maximum value.

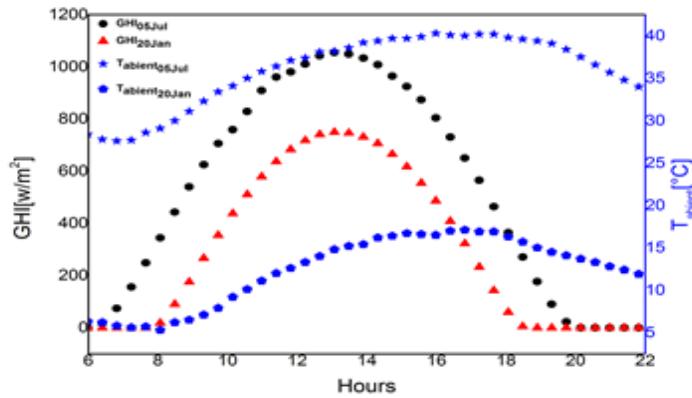


Fig. 6: Ambient temperature and intensity of the overall horizontal radiative flux.

Fig. 7 shows the variation in the temperatures T₂, T₃, T₄, T₅, T₆ and T₇ of the different components in the distiller, namely the temperatures of the basin, horizontal plate, vertical plate, water, inner and outer faces of glass, for the day of July 05. It can clearly be noted that the temperatures follow the evolution of the solar radiation and that the temperature of the plate and that of brine are very close; however, the temperatures of the inner and outer faces of the glazing are significantly lower than that of brine, by 10 to 20 °C. The temperature gradient between glass and brine has a considerable effect on the productivity of the distiller.

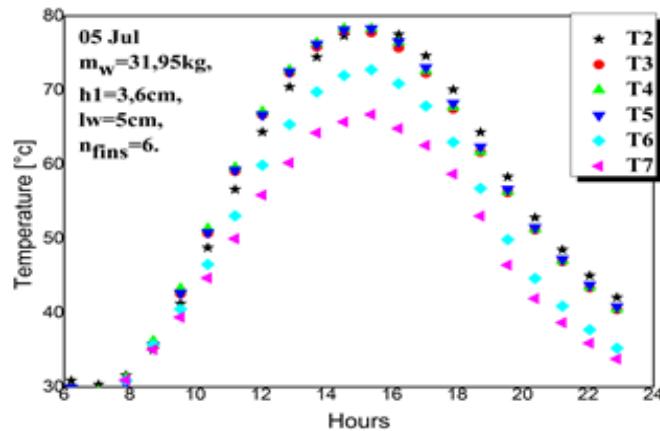


Fig. 7: Temperatures of various distiller components

Fig. 8 illustrates the measured values of the daily production of the distiller from the month of March to the month of August. It is found that the production of the distiller gradually increases to reach maximum values during the months of May, June and July and then begins to decrease after the month of August.

In addition, an average production of 6.6 liters, a maximum production of 8.6 liters and a minimum production of 2.64 liters were recorded. Similarly, Fig. 8 shows the ratio of distilled water production to the daily global horizontal solar radiation (Pr / GHI [ml / Kwh/m²]). It was found that this ratio reaches an average value of 1000 [ml / Kwh/m²].

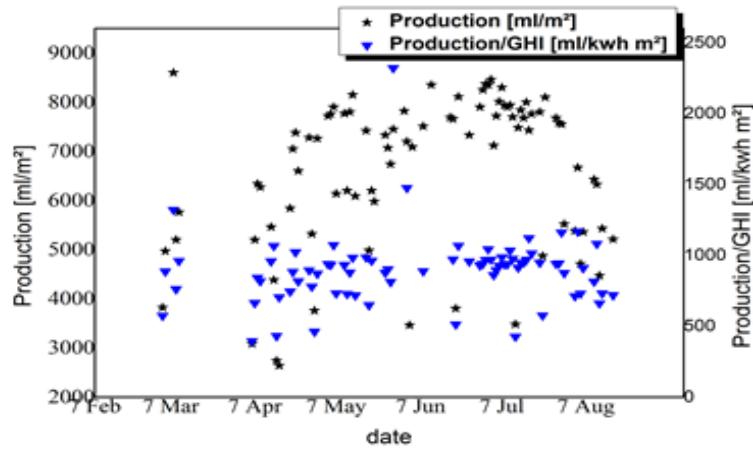


Fig. 8: Daily production of the distiller.

It was found that the temperature of the cover glass coincides with the measured temperature of the inner face of this same cover. As for the temperature of brine, according to the results of Fig. 9, it can be seen that from 8 a.m. to 1 p.m. the mathematical model describes very well the system, and the curves overlap. In the afternoon, the calculated values are slightly higher than those measured. This discrepancy may be explained by the simplifying assumptions made in the modeling of the system.

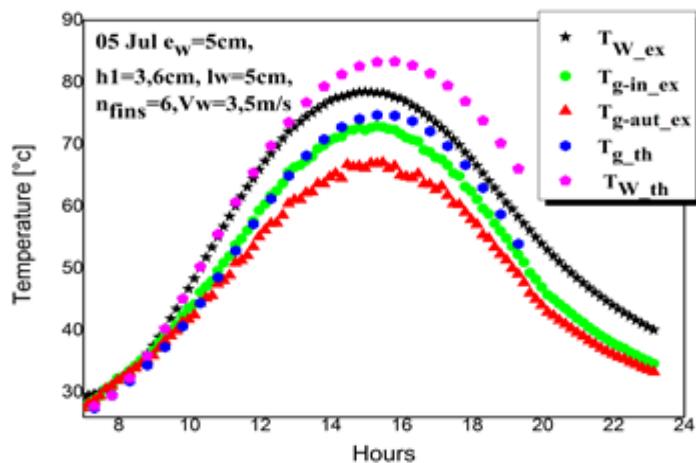


Fig. 9: Comparison of theoretical and experimental results.

Fig. 10 illustrates the production of the distiller for brine thicknesses equal to 2, 3, 5, 6, 7 and 8 cm, corresponding to briny water masses in the basin of 21.3, 31.95, 42.61, 53.26, 63.92, 74.57 and 85.22 kg, respectively. It was found that increasing the water mass in the basin, from 21.3 to 53.26 kg, causes an increase in the productivity of the distiller. Beyond the mass of 53.26 kg, the opposite effect occurs, i.e. the production decreases.

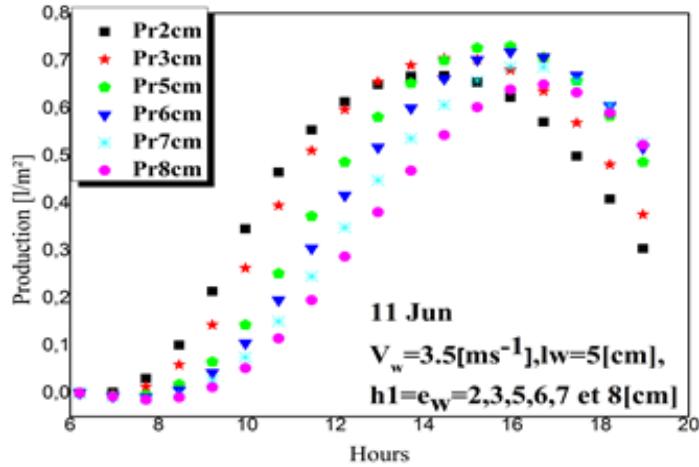


Fig. 10: Production of the distiller for different thicknesses of brine

Moreover, an increase in the wind speed beyond 3.5 m/s leads a decrease in the production of the distiller. This may be explained by the cooling of the system (Fig. 11).

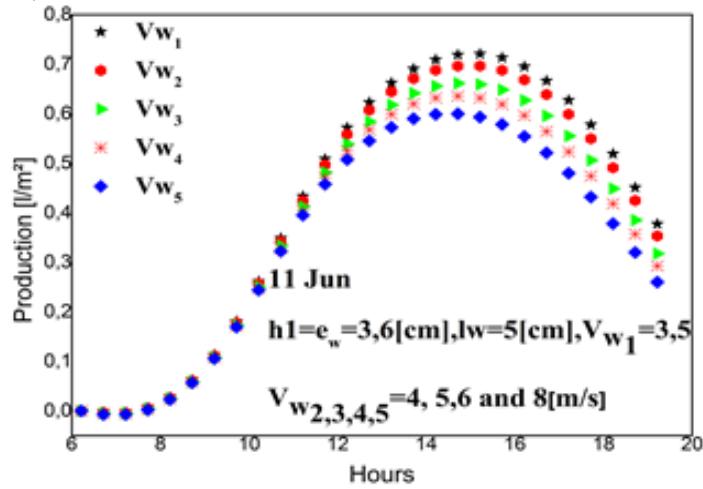


Fig. 11: Influence of wind speed on production

Fig. 12 depicts the production of the distiller for a distance between fins of 5 and 8 cm. In both cases, the brine thickness varied from 3.6 to 5 cm, for the day

of June 11. It was found that the distance between fins does not have a significant effect on the productivity of the distiller.

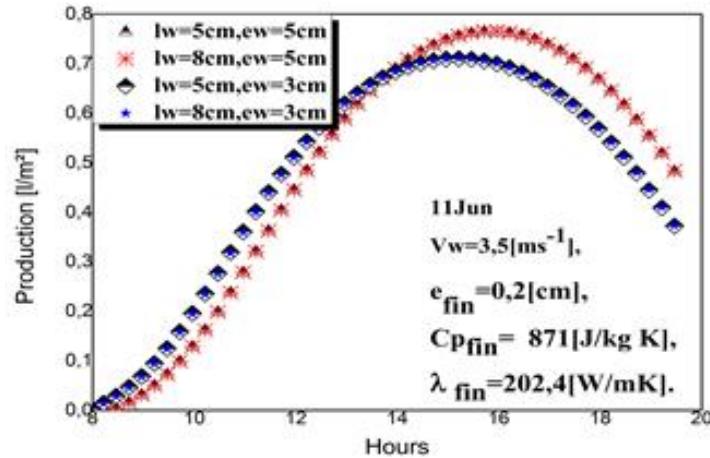


Fig. 12: Influence of the distance between fins on production.

Increasing the number of fins resulted in a rise in the production of the distiller, and this can be explained by the increase in the heat exchange surface since the absorption plate receives a greater amount of solar energy compared to the case without fins (Fig. 13).

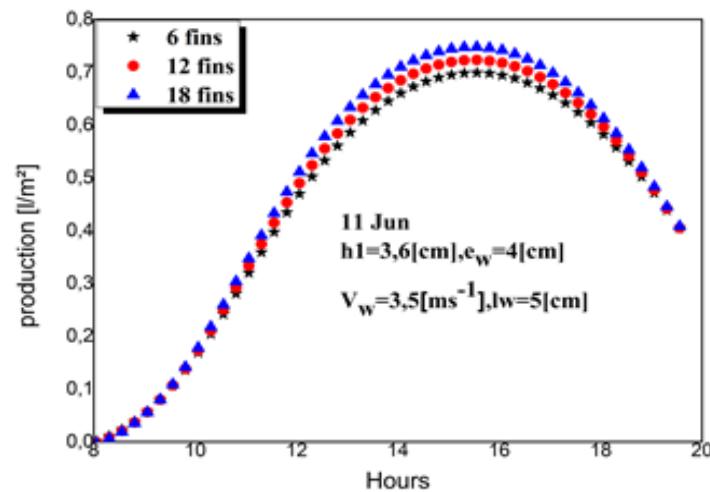


Fig. 13: Influence of the number of fins on production.

5. Cost estimation

The total annual cost is estimated at about 6587.37 DZD, and costs estimation of the various components is given in Table 2. For example, if the

interest rate is 8% and the system life is 5 years, the annual production is close to 2499.5281 kg, gives a product cost of 2.64 DZD.

Table 2

The various components solar still Cost estimation

Materials	Quantity	Price
Polyurethane foam	2	5 000,00 DZD
Silicone adhesive	3	1 200,00 DZD
Glass of 3mm	2m ²	4 915,20 DZD
Resin	5kg	3 000,00 DZD
Glass wool for the thermal insulation (0.05 m thickness)	2m ²	2 000,00 DZD
Labour cost (2 workers, 4 day)		9 600,00 DZD
Total cost		25 715,20 DZD
Various accessories 10%		2 571,52 DZD
The capital cost of the system CC		28 286,72 DZD
Depreciation value S (25% CC)		7 071,68 DZD

Knowing that the average latent heat needed to evaporate one kilogram is 0.65 kWh, we will need 1624.7 kWh to produce 2499.5281 kilograms of distilled water. According to the annual cost of 6587.37 DZD, the cost of one kWh will be 4.05 DZD / kWh. It has been found that the lifetime increasing, and the interest rate decreasing caused a decrease in the unit price. As shown in Fig. 14.

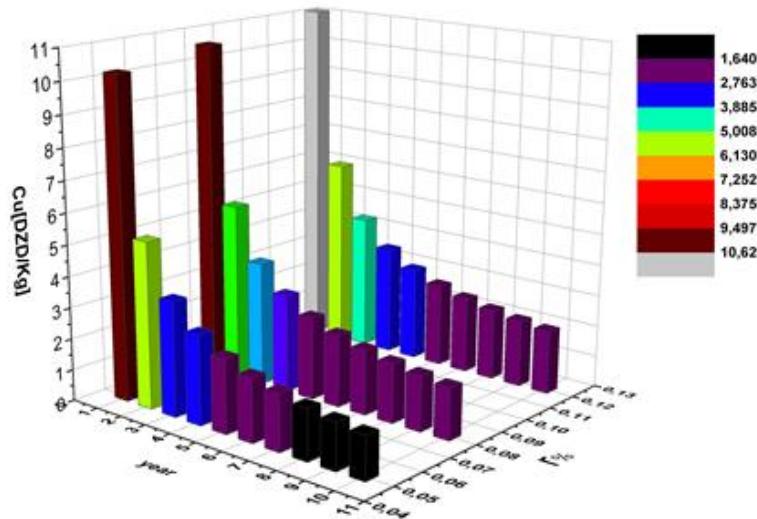


Fig. 14: the lifetime and the interest rate influence on the unit price

6. Conclusion

The present work presents a theoretical and experimental study of a double slope solar distiller, with fins immersed in the basin.

The influence of wind speed, distance between fins, height of fins, the number of fins and the mass of water in the basin, on the production of the distiller was investigated. The results obtained show that when the wind speed is more than 3.5 m/s, the productivity of the distiller drops, as the outer walls of the distiller cool more quickly, and this increases the heat losses from the back and front walls of the distiller. It was found that the distance between fins does not have a significant influence on the productivity of the distiller. Concerning the height of fins, it was established that an increase in the height of fins:

- from 2 to 5 cm, induces an increase in productivity,
- from 6 to 8 cm, induces the opposite effect.

An increase in the number of fins causes an increase in the quantity of distillate. Therefore, it is possible to install the highest number of fins while taking into account the feasibility of the system. The increase in water mass in the basin causes a decrease in productivity. For the day of June 11, and under conditions where $h_1 = 3.6$ cm, $V_{wind} = 3.5$ m/s, $l_{water} = 5$ cm, $N_{fins} = 12$ and for a mass of water of $m_{water} = 21.3, 31.95, 42.61, 53.26, 85.22$ kg, the production of the distiller, with immersed fins, increased by 21, 25, 27, 27 and 15%, respectively, compared to that of a conventional distiller. The estimated cost per kg of distillate was between 10,6 DZD for the first year and 1,6 DZD for ten-year lifetimes.

Acknowledgments

The present work was supported by the solar distillation laboratory at the Thermal and Thermodynamics Conversion Division, within the Research Unit Energies in Renewable Energies in the Sahara Medium. Development Centre of Renewable Energies, Adrar, Algeria.

Authors would like to extend his thanks to URERMS for its support in implementing the project

NOMENCLATURE

Symbol	Index
γ_p	Azimuthal angle of the plane °
γ_s	Solar azimuth °
G_1	Radiation received by a 15 ° inclined plane facing the south
G_2	Radiation received by a 15 ° inclined plane facing the north
G_3	Radiation received by a vertical plane W/m ²
m_w	Mass of water Kg
l_w	Fin width m
l_{wo}	Length of the normal to shaded surface m
l	Length of fins m
H	Height of fins m
N_{fins}	Number of fins
A_p	Flat plat surface m ²
	w Water
	v Vane
	p Plate
	s Saline
	is Isolation
	c Convective
	r Radiative
	e Evaporation
	ar Rear
	ce Sky
	A_{fin} Fins surface

R E F E R E N C E S

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