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Experimental Study of an Inclined Wick Solar Still Operating in Drop by Drop System Under The Climatic Conditions of Hodna's Region, Algeria

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ABSTRACT

Solar distillation is a very economical process for the fresh water production, especially in arid and semi-arid areas where solar energy is abundant. Several types of solar stills have been designed and manufactured for a purpose to increase their performances. This work aims to study experimentally under outdoor conditions of Hodna's region, two types of solar still, the first is an inclined solar still with different wick thicknesses (thick, medium and thin) operating in drop by drop system of feed water and the other is conventional. Four clear days of the April months have been chosen to experiment the solar stills performances. The results showed that the solar stills performances are notably influenced by design and operating conditions, as revealed by the daily production and efficiency values of the inclined solar still with thin wick which achieved 4.14 liter/m^2.day and 46.66%, with an improvement of about 23.21% and 12.56 % respectively, compared to those of the conventional solar still, which reached 3.36 l/m^2 and 34.1% respectively. In addition, the economic analysis illustrates that the low cost of one liter of distilled water and the quicker payback period at the same time are for the inclined solar still with a thin wick of about 0.011$/l and 77 days respectively.

1. Introduction

During the last few decades, the water resources insufficiency has a pressing issue that has affecting roughly a third of the world's population. Projected future developments, such as population growth and increasing climatic and hydrologic variability, are likely to further aggravate water resource scarcity [1,2], because spatial and temporal variations of water demand and availability are large, leading to water scarcity in several parts of the world during specific times of the year [3]. Also, the Global Risk Report 2022 of the World Economic Forum predicts water scarcity as a key driver for migration because of its impact on health and livelihoods as well as the conflicts it risks triggering [4].

Seawater desalination is a solution with great potential since 40% of the world's population lives less than 100km from the sea and 25% less than 25km. It is also a suitable means of providing drinking

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water in areas where natural resources are subject to a salinization effect (rivers, estuaries, inland or underground brackish water, etc.) [5]. But the problem which poses that the energy costs of desalination plants represent the largest part of production cost, for this reason researchers proposed the use of solar energy as an alternative solution which can open up new water sources and contributes efficiently in countries sustainable development [6-11]. The most common type of solar desalination system is the solar still, for its advantages which are: simple conception, economical, require less maintenance, eco-friendly, but the major disadvantage of these devises is the low productivity, so it opens the door for many improvements on it to increase its efficiency and productivity [12-14]. Inclined wick solar still is one of the improvements of conventional solar still [15].

Frick and Sommerfeld designed a solar still with collector-evaporator in wick and plastic cover. Experiments have been carried out on jute, Malve and Canamo wicks. A production rate of 3.8 to 4.4 l/m^2.day and an efficiency oscillating between 40 and 46% were obtained [16]. Yeh investigated the effects of climate, design, and operating conditions on an inclined wick solar still. The author carried out a series of laboratory tests on three stills inclined at 10° to the ground and in which the distances between the wick and the glass are different. The results obtained clearly show that production increases with solar radiation, insulation thickness and ambient temperature. It also appears that the increase in distance between wick and glass, inlet rate of saline water and wind speed, leads to a decrease in production [17]. A new type of still was designed by Minasian and Al-Karaghouli [18]. It is a small conventional solar still, installed in the shade and having an opaque cover cooled by a wet Jute wick, coupled with a solar still with an inclined wick, so that the hot water leaving the tilted wick solar still will continue to feed the conventional solar still through a tube. The experimental study over a year of this new device, showed that it had better efficiency than its two components (conventional solar still, tilted wick solar still), if each operated alone. As for its annual production, the results obtained showed that it exceeded those of tilted wick still and conventional still, respectively by 85% and 43%. Moreover, it has been shown that economically, this new device has better profitability than conventional and inclined wick solar stills. By Basing on the works of Al-Karaghouli and Minasian [19] and Nafey *et al.,* [20], Janarthanan *et al.,* [21] proposed a prototype where in the tilted floating wick solar still, part of the blackened jute wick was placed on a 15° tilted surface and the rest of it is in wavy form floated in water tank, inside the solar still. A water trickle runs down the glass outer surface. The cover temperature decreases significantly, which favors still production, especially during sunny hours. For this prototype, the comparison of theoretical results with those from experience shows a good agreement. An experimental study of an inclined solar still using black cloth and black wool wicks, placed on an absorber plate, was carried out by Aybar *et al.,* [22]. This still was tilted at 30° to increase the amount of solar radiation reaching the absorber. The feed water descends downwards, forming a layer of water over the entire absorption plate. The results show that the use of wicks doubles or even triples the productivity (compared to the still with a plate and without wicks). Tanaka and Nakatake [23] proposed a technique for improving productivity, which consists of integrating a vertical plane reflector, on the upper edge of a tilted wick solar still. The authors noted that using a vertical reflector increases output by about 9%. In another work authors, also conducted a study on an inclined wick solar still with a solar tracking system [24]. Daily production was estimated to be approximately 40%, 57%, 40%, and 27% more than the tilted wick solar still without tracking system, respectively, during the spring equinox, summer solstice, autumnal equinox and winter solstice. Velmurugan *et al.,* [25] tested three stills, in each of them an absorbent material of the same size, but of a different nature (wick, sponge, fin) was used. The results obtained showed that the productivity of the three stills was 29.6%, 15.3% and 45.5% higher than that of the conventional still, using wicks, sponges or fins respectively. Mahdi *et al.,* [26] performed laboratory and outdoor experiments on an inclined wick solar still. The wick used is 100% pure activated carbon cloth, black (no dye is required), and it has a high absorption coefficient, approximately 98% for visible and near IR rays, and 99.0 ± 0.2% for IR rays. Still daily efficiency is 53%, for a clear sunny day in summer, but decreases with increasing water flow rate to be distilled. Another tilted wick solar still was designed and manufactured by Hansen *et al.,* [27]. The authors used various wick materials (polystyrene sponge, coral fleece and wood-pulp paper) on absorber plates, of different shapes (absorber, flat, stepped and stepped with wire mesh). A comparative study was made on solar still performance with different combinations (various wick types and absorber shapes). The results showed that productivity was improved by 71.2% when the combination of a coral fleece wick and a wire mesh absorber was used, with a productivity of around 4.28 l/day. Agboola *et al.,* [28], tested a tilted wick solar still, his daily productivity of distilled water reached 3.25 kg/m^2 with an efficiency of about 40.1%. Sharon *et al.,* [29], studied a stepped wick solar still. They depicted that the productivity of tilted solar still was nearly 19.76% higher than that of the unit with wick without inclination. Zoori *et al.,* [30], tested weir-stepped solar distiller and got the maximum exergy and energy efficiency as 10.5% and 83.3% respectively. Productivity improvement was found as 86.91% as compared with conventional solar distiller [31].

In this experimental study, an attempt was made to maximize the evaporative ratio by improving the method of feed brackish water to keep the wick wet on the one hand, and to reduce their influence on wick temperature on the other hand. This objective was achieved by using a feed water system which operating in drop by drop. The system is very simple and economical, it formed as a water tank connected with a tube with multiple holes put down along the solar still. In addition, we use glass as lateral walls to eliminate the shading effect of them, which reduce the amount of solar radiation reached the wick.

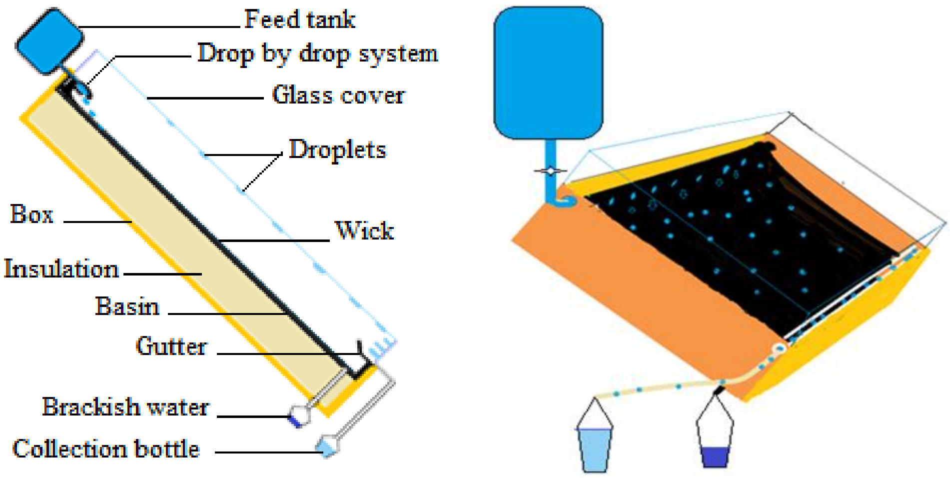
Solar still enhancement is demonstrated through a comparative study between conventional (CSS) and inclined wick (IWSS) solar stills. The stills were designed, manufactured and tested under the same operating conditions for clear days at the laboratory of physics and chemistry of materials, university of M'sila, Algeria. Also, Economical study of the stills is conducted to estimate the cost of one liter of distillate water and the payback period of the modified and conventional stills.

2. Experimental Work

2.1 Solar Still Description

Solar still used in this study has a very simple design as shown in Figure 1. It was made with cheap materials and easily obtainable in the local market. This modified solar still is consisting of a transparent cover, a blackened wick, basin, an insulated base, and overall framework. The overall framework is 980mm×480mm×140mm wood with 40mm thickness, and the insulation at the bottom consists of 60mm thickness polystyrene layer between the sheet of wood and the basin. Three wicks with different thicknesses in black cotton are used: thick cotton, fine cotton and medium cotton, with 900mm length and 400mm width. At the top edge of wick, the system of drop by drop was attached. This system is formed as a water tank installed in a high place and connected with a tube with multiple holes put down along the solar still.

For transparent cover, ordinary glass of 4mm thickness was chosen because of long life, cheaper, available, and their physical and chemical characteristics do not change with weather conditions. It is fixed on the above edges of the framework, and made from five glass sheets with different dimensions. The first on the top with 940mm length and 440mm width, and the others on sides with 100mm heights. This design makes it possible to reduce the distance between evaporating (wick) and condensing (glass cover) surfaces and keep the best still inclination at the same time. Also, it will reduce the height of the side walls of cover which are in glass to eliminate the shadow effect on these sides. The distiller is sealed using silicone, to avoid water vapor leakage.



(a) (b)

Fig. 1. Schematic diagram of the inclined wick solar still operating in drop by drop (a) side view (b) front view

2.2 Working Principle

Figure 1 shows the operating principle diagram. In the tilted wick of the modified solar still, feed water flows slowly through a porous filling (wick), which absorbs solar radiation. This type of distiller has two essential advantages. First, the wick was tilted from the horizontal level, so that the feed water has a better angle with the sun (reducing reflection and presenting a large effective surface area). Second, less feed water in the solar still at any time. So, the water is heated more quickly and has a high temperature, resulting in a large amount of vapor in a short time. This water vapor produced leaves the wick and will condense on contact with the glass cover. Distillate and residual water are collected by bottles.

2.3 Experimental Setup

The solar still was built and tested at the faculty of Sciences, University of M'sila, Algeria (altitude 441m, latitude 35°70' North, longitude: 4°54' East). This region has a continental climate partly subject to Saharan influences. The summer is dry and very hot, while winter is very cold.

The tests were carried out at the month of April 2018 and the experimental data presented in this study concerns four typical days. The feed brackish water to the solar still is done by a system that works drop by drop from a water tank, to ensure that the wick remains wet all the time. The wick solar still is placed on a tilted support with an angle equal to the latitude of M'sila site (36°), and oriented in the north-south direction to receive the maximum amount of solar radiation during the day.

The temperatures of: wick (T_w), glass (T_{gl}), basin (T_b) and ambient (T_a) are measured by digital thermometers. Humid air temperature (T_{vap}) in the wick and conventional solar stills is also measured using a digital thermo-hygrometer. Global solar radiation and wind speed were obtained from the Msila weather station. A glass graduated bottle of 1 liter was used to collect and measure condensate production, and another bottle placed under the still was used to collect brine. All measured parameters were recorded (direct reading) every half hour from 7:00 a.m. to 5:00 p.m.

(a) (b)

Fig. 2. A photograph of the test-rig setup (a) inclined wick solar still (b) conventional solar still

3. Results and Discussion

3.1 Meteorological Parameters

Atmospheric conditions during the test days, namely: global solar radiation and wind speed are shown in Figure 3 and Figure 4.

3.1.1 Solar radiation

Figure 3 shows the evolution of solar radiation for all test days for the month of April as a function of time. It is observed that the solar radiation increases with time to reach the highest limit at 12:00h, then it is reduced at the end of the day. Global solar radiation for the month of April was in the range of 0-880 W/m^2 with a sunshine duration of about 12h.

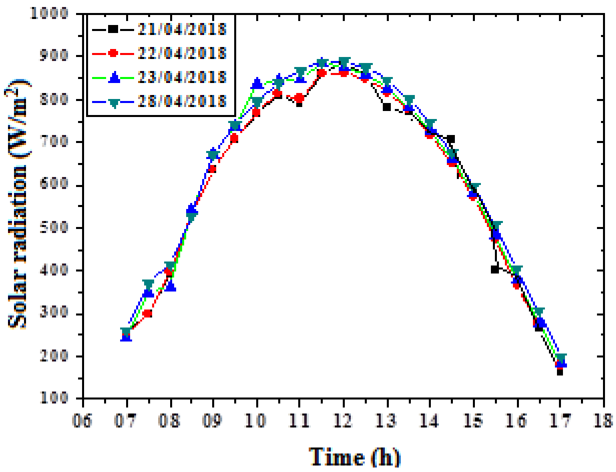


Fig. 3. Variation of solar radiation

3.1.2 Wind speed

Figure 4 shows that the wind speed is unstable. It varies rapidly and randomly. It reaches about 6 m/s. In fact, wind increases the heat transfer by convection between the glass cover and ambient [32,33]. This causes a decrease in the glass cover temperature, which increases condensation, and accordingly improves the distiller productivity.

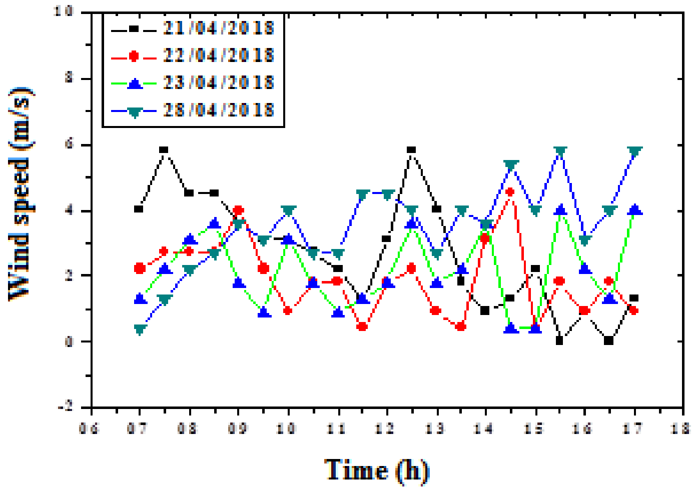


Fig. 4. Variation of wind speed

3.2 Solar Still Components Temperatures

Figure 5 to Figure 8 shows variations in temperatures of the glass cover, wick, basin, water vapor in wick solar still and water temperature of conventional solar still. First, the effect of atmospheric conditions on solar still thermal behavior is apparent on the variation of temperatures during the test days. It is shown that, in the morning from 7:00 to 11:00h, all temperatures increases at a faster rate of about 30°C during this period, and then it peaks between 12:00 and 13:00h. Temperature of glass inner surface is exceeded 50°C. The elevation of the latter is due to the absorption of incident solar radiation and the heat given up by the evaporating surface (the wick) by radiation, evaporation and natural convection. Finally, the temperatures are reduced slowly compared to the morning, this due to the thermal inertia of the components of the solar still. The ambient temperature increases over time and goes from 20°C to about 30°C. It has effects on the glass temperature (especially by natural convection), which directly affects the solar distillation process.

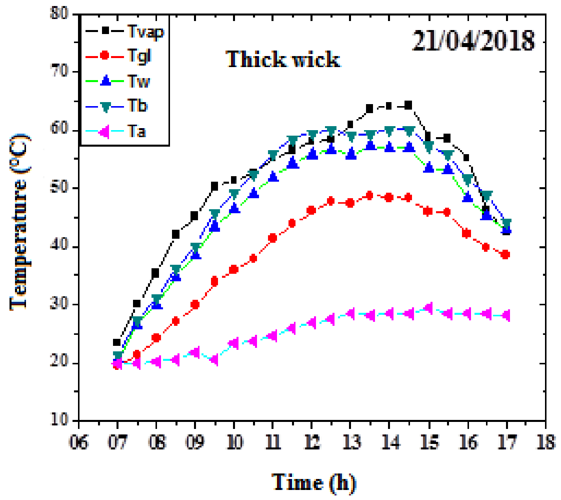


Fig. 5. Variation of solar still components temperatures with thick wick

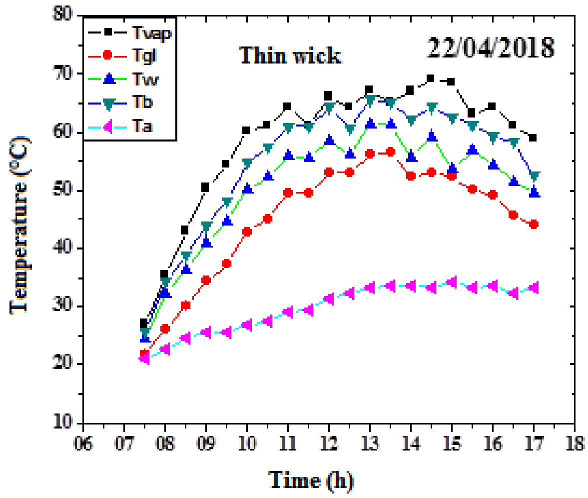


Fig. 6. Variation of solar still components temperatures with thin wick

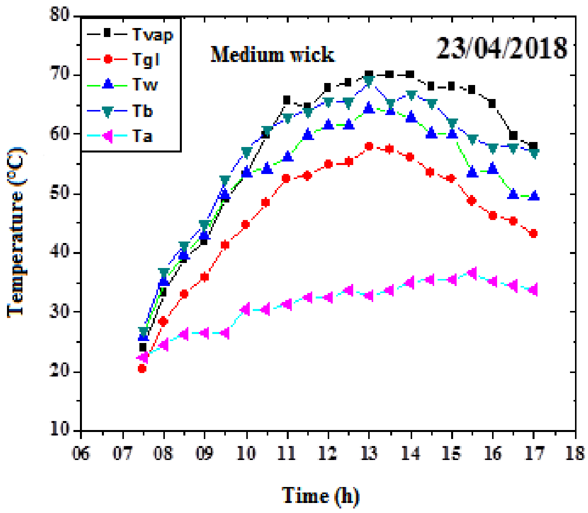


Fig. 7. Variation of solar still components temperatures with medium wick

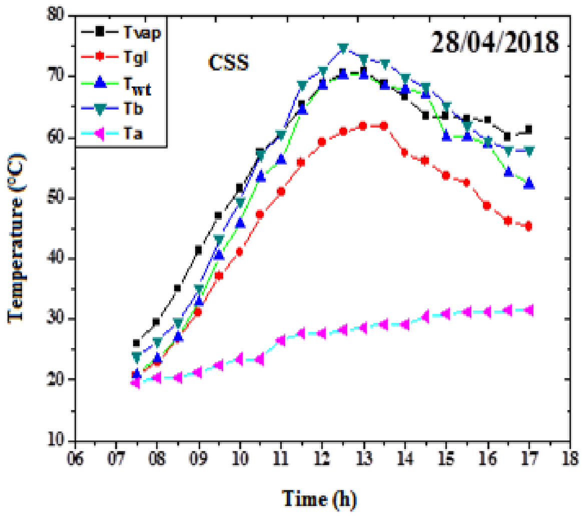


Fig. 8. Variation of conventional solar still components temperatures

3.3 Accumulated and Hourly Yield

Variations of accumulated and hourly yield of all the cases studied are presented in Figure 9 and Figure 10. The comparison shows that tilted wick solar still production is better than that of conventional still, where daily productivity of conventional solar still is about 3.4 l/m^2, while for the modified solar still it reaches 4.14 l/m^2, with an improvement of 23.21%. This is mainly due to the effect of using tilted wick and drop by drop system on the one hand, and the glass cover conception of wick solar still which reduce the space between the evaporation surface (wick) and condensation surface (inner glass cover surface) in comparison with conventional solar still. The performance of the solar still increases when the evaporation surface and glass cover distance decreases, this because of the heat and mass transfers in a solar still using the greenhouse effect, only occur at the level of a thin adjacent layer of the evaporation surface to the condensation surface, everything else, constitutes a layer called the Buffer layer, which is a layer having a constant temperature and not participating in the various transfers. Consequently, an increase in height increases the thickness of the buffer layer which tends to oppose the exchanges between the condensation surface and the evaporation surface. Hourly production curves show that wick solar still production starts before the conventional still, and it is high for modified solar still compared to that of conventional from 13:00h.

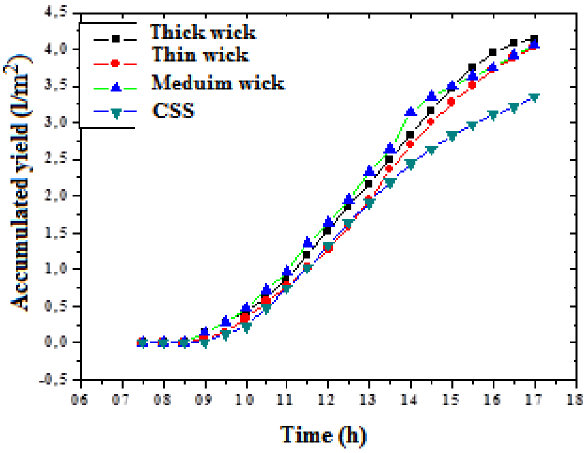


Fig. 9. Solar stills accumulated yield

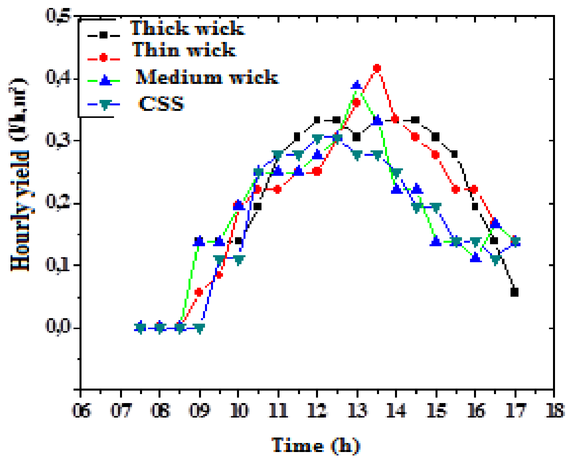


Fig. 10. Solar stills hourly yield

4. Solar Stills Efficiencies

The daily thermal efficiency of conventional and inclined wick solar stills is calculated respectively as follows

$$\eta_{daily.th} = \frac{\sum \dot{m}_{ev} h_{fg}}{\sum I(t) A_s \times 3600} \times 100$$

where; A_s is the absorber area (m^2); *I(t)* is the solar radiation (W/m^2); $\dot{m}_{ev}$is the hourly distillate yield, (kg/m^2.h). Results are presented in Table 1.

Table 1
Daily thermal efficiencies of stills

Stills	$\eta_{daily.th}$
With thin wick	46.66%
With medium wick	44.73%
With thick wick	39.27%
Conventional	34.1%

5. Economical Study

Different parts and overall system prices are detailed in Table 2.

Table 2
Fabrication cost of conventional and inclined wick solar stills

Unit components	IWSS	CSS
Glass cover	980 DZD (7$)	600 DZD (4.28$)
Framework	1500 DZD (10.71$)	1900 DZD (13.57$)
Silicone paints	250 DZD (1.78$)	250DZD (1.78$)
Insulation	400 DZD (2.85$)	700 DZD (5$)
Pipes and valve	280 DZD (2$)	200 DZD (1.42$)
Galvanized plate	400 DZD (2.85$)	400 DZD (2.85$)
Black coating	400DZD (2.85$)	400 DZD (2.85$)
Wick	175 DZD (1.25$)	----
Paste glue	80DZD (0.57$)	80 DZD (0.57$)
Total fixedcost	4565 DZD (32.60$)	4530DZD (32.35$)
Total fixed cost per m²	12680.55 DZD (90.57$)	12583.33 DZD (89.88$)

Economical study of the solar stills is based on the work of Munisamy *et al.,* [36] who made a detailed economic analysis of the different solar distillation systems including the parameters that influence the cost of the distilled water produced. The calculated parameters are included in the following Table 3.

Table 3
Economic analysis of solar stills

Parameters	Formula	Still with thick wick	Still with medium wick	Still with thin wick	Conventional solar still
CRF (capital recovery factor)	$\mathrm{CRF} = \frac{r \times (1+r)^n}{(1+r)^n - 1}$	0.177	0.177	0.177	0.177
SFF (sinking fund factor)	$\mathrm{SFF} = \frac{r}{(1+r)^n - 1}$	0.057	0.057	0.057	0.057
P (total fixed cost)		12680.55 DZD (90.57$)			12583.33 DZD (89.88$)
FAC (fixed annual cost)	FAC= CRF× P	2244.257 DZD/year			2227.05 DZD/year
S (salvage value)	S = 0 ,2×P	2536.11 DZD			2516.666 DZD
ASV (annual salvage value)	ASV=SFF*S	144.518 DZD			143.41 DZD
M (average annual productivity)	M = daily productivity×340	4.03*340= 1370.2 l/year	4.06*340=1380.4 l/year	4.14*340=1407.6 l/year	3.36*340=1142.4 l/year
AC (annual cost)	AC=FAC+ AMC- ASV	2324.16 DZD/year			2306.345 DZD/year
CPL (cost of distilled water perliter)	CPL=$\frac{\mathrm{AC}}{M}$	1.696 DZD/l (0.012 $/l)	1.683 DZD/l (0.012 $/l)	1.651 DZD/l (0.011 $/l)	2.018 DZD/l (0.014$/l)
Payback		79 days	78 days	77 days	95 days

Where *n* and *r* are the expected lifetime (10 years) and the interest rate (12%) respectively

From economic analysis (Table 3), it has been found that the distilled water cost per liter of inclined solar still with different wick thicknesses is 0.012$/l (for thick and medium wicks) and 0.011$/l (for thin wick), however for conventional solar still is 0.014$/l. The average productivity of inclined solar still with thin wick remains higher as compared with others. Consequently, the payback period is only 77 days, whereas for conventional solar still it is 95 days.

6. Comparison with Previous Works

A comparison between this work and another's of an inclined wick solar still reported in the literature is presented in Table 4. Results illustrate that this proposed system has a competitive performances compare with others.

Table 4
Comparison of present work with inclined wick solar still in literature

Stills	Ref	Improvement	Efficiency	Cost per 1 liter
Tilted wick solar still	Sharon *et al.,* [29]	during April 4.54 l /day	33.83%	0.046 $/l
Cloth moving wick type solar still	Gad *et al.,* [34]	Low productivity	About 40%	---
Tilted wick still	Manikandan *et al.,* [35]	----	39.39%	---
tilted-wick still	Munisamy *et al.,* [36]	3.63 l/m² day	---	---
Solar still with tilted wick coupled with flat plate collector	Negi *et al.,* [37]	3.997 kg/m^2 day	---	---
Present work		4.14 l/m^2day	46.66%	0.011 $/l

7. Conclusion

Experimental study and comparison between an inclined solar still with different wick thicknesses operating in drop by drop system and conventional solar still, under the climatic conditions of Hodna's region, have been presented. From the results achieved in the present research work, the following conclusions are arrived

i. The best daily output is obtained from tilted solar still with thin wick, which reached 4.14 l/m^2, with an increase of about 23.21%.
ii. The daily efficiency for inclined wick solar still is from 39.27% to 46.66%, whereas for the conventional solar still is 34.1%
iii. The lowest distilled water cost and payback period obtained from the tilted solar still with thin wick are estimated at 0.011$/l and 77 days, whereas those of the conventional solar still are about 0.014 $/l and 95 days.
iv. The performances improvement of the proposed solar still are obtained for several reasons, the most important of which are
    - The use of drop by drop system (low flow) reduce the effect of feed water temperature on the evaporation surface temperature.
    - Elimination of shadow effect from side walls.
    - The inclination angle of wick solar still was equal to the experimental site latitude [7].
    - Placing the solar still glass cover parallel to the evaporation surface (wick) to minimize reflection losses [38].
    - The capillary effect of wick contributes efficiently to enhance the evaporation rate.
    - Reducing the gap distance between evaporation and condensation surfaces was increased the performance of the solar stills, because the increase of air gap results an increase in the difference between the evaporating and condensing surface temperatures, and a decrease in the internal heat transfer coefficients by convection and evaporation [39]. The

glass temperature is decreased by increasing the amount of heat dissipated from the glass cover to the ambient [40].

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