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Parameters of construction, positioning, orientation and those of adequate operation of a solar distiller in the south east of Algeria

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ABSTRACT

Some residents of southeastern Algeria have heard of solar stills and their use as simple devices to purify the brackish water that is abundantly found in this region. In view of putting an end to the lack of drinking water, the residents turned to the Process Engineering Laboratory at Ouargla University to have answers to questions that concern them, such as the design of these devices and their operating parameters. The task is then entrusted to three Master's students to answer their questions. The students designed for this investigation four simple single-slope stills and highlighted the study of some key parameters that make the use of these devices efficient. Their investigation then focuses on certain parameters, namely: the inclination and thickness of the glass cover, the depth of the brackish water, the geographical orientation of these distillers, and the influence of certain climatic parameters such as solar intensity and wind speed. The results obtained show that the optimal thickness of the glass cover is 4mm, tilted by an angle of 30° with a brackish water depth of 0.5 cm; the device will be placed towards south direction facing sun with high wind speed location. The average gains are: 40% for south orientation compared to the north; 34.38% for 4mm thickness compared to other thickness; 8.52% for the minimum water depth of 0.5 cm and 31.2% for the air speed of 4.3 m/s. Finally, we obtain distilled water with 96% purity and we advise users of solar stills to add an adsorbent or a photocatalyst to the water in the basin to get rid of all organic impurities accompanying distillate.

Keywords: Solar still; Brackish water; Inclination; Depth; Thickness; Wind speed; Orientation; Algeria.

1. Introduction

The planet earth, despite its enormous wealth in water, remains poor in drinking water since more than 97% of this water is salt water found in the seas and oceans. The recent population explosion is confronted by an alarming shortage of drinking water [1]. The arid and semi-arid regions in the south of Algeria are supplied by brackish water, given its enormous reserve estimated at (60×10^3 billion) m^3 despite its high salinity rate, which can exceed 8 mg/L in certain places [2,3]. The use of fossil energy to produce drinking water is expensive and polluting; so, in recent years, we have looked into the use of another source of energy that is less expensive and non-polluting, it is solar energy [4].

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Solar distillation has become the perfect replacement for other processes that consume fossil energy. It is recommended for use on a small scale in rural and strongly sunny regions such as the Ouargla region, where sunshine is estimated at (2,700 kWh/y·m^2) [3,5].

Despite the advantage of solar energy, the efficiency of simple solar stills remains low, and their production is always insufficient [6,7]. From this, several investigators have tried to improve their performance by carrying out theoretical and experimental studies involving several key parameters, whether design, climatic or operational.

The design of a simple distiller is very simple; it is a metal basin enclosed in a wooden box and perfectly insulated from the outside and whose cover is a transparent glass. The saline water contained in the basin absorbs heat via the sun's rays, evaporates, and condenses on the cover to be collected separately [8].

The design parameters of simple stills are deeply studied by several researchers in the world in order to find an optimum for each parameter, thus allowing for improving the performance of such devices [9].

Heat loss to the outside is a very important design parameter based on the nature and thickness of the layer isolating the basin from the outside.

Several insulating materials have been tested in this area; their choice is generally based on the thermal conductivity, which must be very low, and their mechanical flexibility to cover the basin in a watertight and adequate manner [10].

The tilt angle of the glass cover is also an important design parameter which is directly related to the sun. The height angle of the sun depends generally on the geographical position of the place of study. For the solar rays to be perpendicular to the still, the glass cover must be inclined by an angle that depends on the height of the sun. In this context, some research has taken place. Cherraye et al. [11] carried out work aimed at finding the appropriate angle of inclination for the glass cover according to the seasons in Ouargla city. They found that the angle of inclination is close to the height of the sun; they then deduce that the operating angle is around 30° during spring, the recommended season for high productivity.

From its name, it seems that the climatic parameters of the operational place are predominant for a solar distiller, which is supplied energetically from the sun; then, the intensity of the solar rays is the energy generator of the distillation operation.

Sunny regions are always those recommended for the location of these devices. Research has shown that the production of distilled water is directly proportional to solar irradiance [12]. However, in some cases, the high intensity can cause internal overheating and disturb the condensation of vapors; hence, the use of internal energy storage tanks like sand, gravel, sponge, becomes a necessity, as we will see next.

To enhance the productivity of these devices, researchers proposed several types of solar stills: multiple-effect solar still [13], cascaded type [14], inverted absorber type [15], multiple-wick [16], vertical type [17], conical type [18], triangular pyramid [19], tubular type [20], double condensing chamber [21] "V" type [22], etc. The ambient temperature is also one of the climatic parameters influencing the yield of the distillation; the low temperatures of the ambient air lead to a cooling of the glass cover which favors a good condensation of the ascending vapors from the basin. From this, we can conclude that in summer, solar distillation is not really profitable in hot and strongly sunny regions, given the internal overheating and the external contact of the condenser with the warm ambient air [10].

In all the articles published for years by the researchers of the process engineering laboratory of Ouargla University, the experiments were carried out in the spring when the sunshine was moderately acceptable, and the ambient temperature was not high [23].

Since the difference between the temperature of the basin and that of the cover directly reflects the rate of condensation of the vapors; then, it is advantageous to increase this difference to improve the yield of the distillation. So, the decrease in the condenser temperature is a positive index, thus favoring condensation [24]. The speed of the air outside contributes to increasing the exchange coefficient by convection between the ambient air and the condenser. Nevertheless, the results found by the investigators show that low wind speeds do not have a significant effect on the stills' performance [12].

To increase basin temperature, some investigators coupled the still with other devices such as concentrators [25], solar heaters PV/T [26], solar chimney [27,28], and geothermal sources [29,30].

The design parameters are fixed from the beginning by the designer, while the climatic parameters are natural; then, the only parameters available to be varied are the operating parameters; these parameters are those that have attracted the most attention from researchers given their diversity, which has consequently led to the development of several ideas all aimed at overcoming the disadvantages and also helping to improve the performance of these devices.

The depth of the water in the basin is another dominant operating parameter that has taken the attention and concern of researchers in this field [31]. Since the quantity of heat received by the basin is constant for a given distiller, the temperature of the saline water therein depends on water quantity. Given that the surface of the basin is constant, the temperature of the saline water is inversely proportional to its quantity, in other words to its depth. So, depth is one of the major operating parameters influencing distiller productivity. Low depths generally reduce the waiting period and speed up the distillation process. In this area, several works have been published by researchers who have all agreed on the fact that solar distillation is effective when the depth of saline water in the basin is low between 0.5 and 2 cm [10,12,24].

To increase the absorption of solar rays by brackish water, some researchers have added a black substance to it; it is either black ink or bitumen or finely ground coal [32,33]. Ali Ouar et al. [3] found that the layer of 0.5 cm of Bitumen increases the yield by 25.35% while the addition of 0.6038 kg of coal per square meter of absorber surface and adding 10 drops of black Chinese ink separately improves the gain by only 18.42% and 6.87%, respectively.

To reduce energy losses and extend the distillation period in the absence of sunlight, some investigators have created heat storage mediums within the basin.

Sellami et al. [10,12] used a layer of blackened alluvial sand, a mixture of alluvial sand with Portland cement; they obtained an improvement of 43.51% and 39.07% in the yield of distillate, respectively.

Sellami et al. [24] used Portland cement in its two states: layer and powder; they obtained improvements in the production of 51.14% when using 0.906 kg of powder cement per square meter of absorber area.

Blackened layers of sponge are also used as heat storage medium [34,35]. Sellami et al. [36] found that 0.5 cm sponge thickness increased the yield by 58%, relative to the baseline case; in contrast, a sponge thickness of 1.0 cm resulted in a yield improvement of only 23%, whereas a sponge thickness of 1.5 cm resulted in a decreased yield of 30% relative to the baseline case.

The use of gravel is also another technique adopted by several investigators. Ouar et al. [37] used a pre-optimal mass of 1.25 kg of black granite, that is, 5.48 kg of granite m^{-2} of absorber surface; it contributed to 4.135 $kg \cdot m^{-2} \cdot d^{-1}$ of distillate with an improvement in profitability by 34.09% compared to the baseline case.

Photocatalysis plays a very important role in solar distillation, either on the quantity or quality side; the use of semiconducting metal oxides is another technique applied by several researchers [38–43]. Labied et al. [44] used (CuO), (Fe_2O_3), and (ZnO) with different weight concentrations. Their experimental results reveal that those semiconductors play the role of photocatalysts. The productivity increases by 22.43%, 16.64%, and 13.02%, respectively, compared with the conventional still for a weight concentration of 0.16% of semiconductor and 1 cm of brackish water depth.

Kouadri et al. [23] used 20 g of ZnO and 20 g of CuO separately in two different stills, each containing 3.6 L of brackish water; the daily production was improved by 79.39% and 74.76%, respectively compared to the baseline case; additionally, photocatalyzed units produced a high-quality distillate.

In this work, and although the simple solar still has been extensively studied by many researchers, we will never be able to project their results on our case since the climatic and operating conditions differ from one region to another; it is for this reason that we would like to use our own results those found here in Ouargla and which are adequate with our location and our treated water. From here, we started from zero by analyzing all parameters namely: climatic parameters, design parameters and operating parameters. So the study focuses on the effect of the following key parameters: solar intensity, wind speed, geographical orientation of the still, the thickness of the glass-cover, its inclination and the depth of the brackish water.

2. Experimental set-up

2.1. Construction of solar stills

To answer the questions of some residents about solar stills: their design, their mode of operation, their location, and their performance. Three Master's students belonging to the laboratory of process engineering at the University of Ouargla manufactured 4 simple distillers with a single slope of 4 mm thick galvanized basins (60 cm × 40 cm × 5 cm) insulated by a layer of 4 cm thick of polystyrene and enclosed in a wooden box and topped by 4 mm thick transparent glass. The glass cover is inclined by 30° compared to the horizon. The assembly is well glued by silicone to avoid any probable leakage. The distillers are placed facing the sun towards the south direction. Fig. 1 shows the type of the still used in experiments.

2.2. Measuring tools

Several instruments are used in this experimental study to measure the physical parameters of brackish and distilled water and some meteorological parameters.

- Solar meter to measure the solar intensity (W/m^2).
- Thermocouples (K-type) for measuring temperatures (°C).
- Hygrometer for measuring the relative humidity (%) and the ambient temperature (°C).
- Hot wire anemometer for measuring the wind velocity (m/s).
- Graduates tubes for measuring the distilled water volume (mL).
- Multi-parameter (Hanna – HI 9829, HANNA Instruments France) for measuring the physic parameters of water, namely: the pH, electric conductivity (µs/cm), and salinity (ppm).

The accuracy, range, and errors of the measuring tools are presented in Table 1.

Fig. 1. Photo of the type of distillers designed.

Table 1
Accuracy, range and error limit for different measurement devices

Instrument	Accuracy	Range	Error %
Anemometer	+0.1 m/s	0–40 m/s	1.5%
Thermometer	+0.01°C	0°C–300°C	1%
Thermocouple	+0.1°C	0°C–100°C	1%
Solar meter	+1 W/m^2	0–1,500 W/m^2	<3% ± 1
Graduate tube	+10 mL	0–1,000 mL	1%

3. Experimental procedure

During this work, four experiments were carried out, preceded by measurements of certain meteorological parameters, namely: solar intensity, ambient temperature, and wind speed.

The results obtained during the experiments are presented in the form of graphs. In this paper, we have not presented all the graphs because of their large number, but we have tried to present samples of different graphs in each experiment. The experiments were redone 3 times for 3 consecutive days from 09 a.m. to 05 p.m. to better concretize the results.

We note here that the experiment of the glass-cover tilt angle carried out by Cherraye et al. [11] for the area of Ouargla founded on former results was not redone, which leads us to use the value of 30° as the experimental angle of inclination.

3.1. Effect of glass-cover thickness

Three solar distillation units were designed for this study with different glass thicknesses: 3, 4, and 5 mm maintaining their inclination at 30°; hourly production and daily yield have been monitored to see which of the thicknesses gives the best result.

3.2. Effect of brackish water depth

In this experiment, shallow depths were chosen: 0.5, 1 and 1.5 cm. The temperature of the absorber is noted each hour with that of the glass cover, and the volume of distilled water collected and the daily yield of the distillate has also been monitored.

3.3. Effect of the sense of geographical orientation

Here, we placed the four units facing the four known geographical directions: North, South, East, and west; each time, the hourly and cumulative production is measured to confirm which direction is the most favorable to obtain high efficiency.

3.4. Effect of the ambient air speed

In this experiment, our goal is to see the effect of the external air speed on the yield of the distillation by using 3 fans at different speeds, and we compare the results with those of the witness, which remains without ventilation.

4. Results and discussions

To avoid any repetition, the error and uncertainty for each measured value is mentioned in the Table 1.

4.1. Weather parameters

We will present here only the known parameters, such as solar intensity, ambient temperature, and wind speed.

Figs. 2 and 3 display the variation of solar irradiance, ambient temperature, and wind speed, respectively vs. local time for the day of February 08/2022.

As shown, the solar irradiance recorded at 09 a.m. is 333 W/m^2; it reached its maximum value of 751 W/m^2 at mid-day.

In this period, the solar intensity is moderately high because the environment is clear, so it is a suitable period for solar distillation in Ouargla city.

The average ambient temperature measured is 22°C; this is a low value that contributes better to the cooling of the glass cover and therefore leads to a good distillation yield.

Wind speed is an unstable quantity that does not follow any logic. Sometimes it is high, and sometimes it is low; in our case, it fluctuates between 1 and 3.25 m/s.

4.2. Effect of glass-cover thickness

The glass cover receives the sun's rays; one part of these rays is reflected, another is absorbed, and the majority (more than 80%) is transmitted to the basin.

The thickness of the glass cover can then play a role in the variation of the quantities of rays whether reflected, absorbed, or transmitted; from here, we can deduce that the solar intensity reaching the brackish water depends on the thickness of the glass cover.

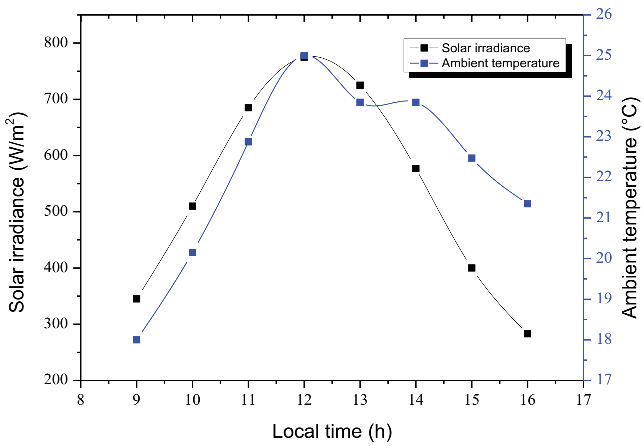

Fig. 2. Solar irradiance and ambient temperature vs. local time (Feb/08/2022).

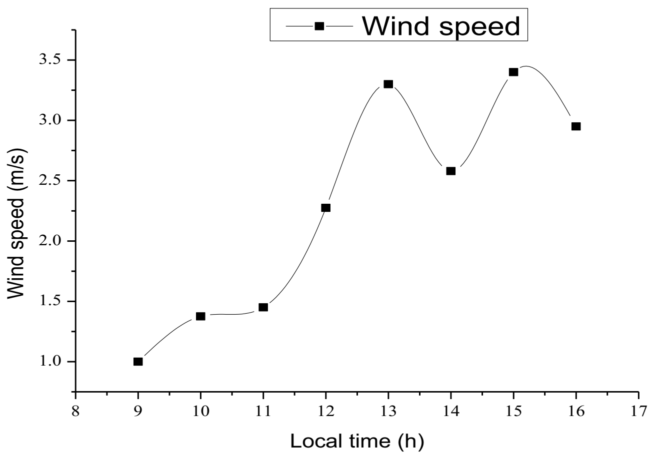

Fig. 3. Wind velocity vs. local time (Feb/08/2022).

The cumulative production of the three units having covers of different thicknesses 5, 4, and 3 mm (available in the market) is represented in the form of graphs.

From Fig. 4 it can be seen that the still of 4 mm thick glass cover produces better than the 3 mm and 5 mm thick ones.

The explanation is simple and logical since it is based on the flow of rays reaching the water. When the thickness is 5 mm, the transmittance is insufficient, and the water takes a long time to heat up; contrary to the case of 3 mm, the quantity of heat transmitted by the rays is very important, even excessive heat that causes around mid-day and internal overheating; thus leading to poor condensation because of the internal overheating of the glass cover. The 4mm thick case seems optimal and then leads to a significant production of distilled water.

Daily yield collected for the stills with different glass cover thickness is 2.601, 1.961, and 1.910 L/m^2 of absorber area for the thickness of 4, 5, and 3 mm, respectively, at the beginning of February 2022.

The average gain in distilled water compared to the other two thicknesses exceeds 34.38%.

4.3. Effect of brackish water depth

Since the basin area is constant, the volume of brackish water in the basin depends on its depth; then, according to Table 2, if the depth is: 1.5, 1, and 0.5 cm, the volume of water contained is respectively: 3.6, 2.4, and 1.2 L.

Since the quantity of heat received by the absorber is identical in the three units, the quantity of 1.2 L heats up and evaporates before the other quantities; otherwise, the unit of 0.5 cm of water depth produces more distilled water than other units with depths greater than 0.5 cm; then, we can conclude that the production is inversely proportional to the depth of brackish water in the absorber.

Fig. 5a shows the temperature difference between the absorber and the condenser during the experiment for the different depths mentioned; this difference directly reflects the rate of evaporation and condensation of the steam; in other words, it reflects the amount of distilled water collected.

This temperature difference is directly proportional to the quantity of distillate produced, which will be confirmed by the hourly and cumulative production curves.

Fig. 5b displays the hourly production for the three units vs. local time; it is clear that the unit of 0.5 cm of water depth remains better from 09 a.m. to 16 p.m., followed by units with 1.0 and 1.5 cm depth. The hourly yield which we will clear and confirm this fact.

Fig. 5c presents the hourly cumulus of the three tested units; here, the difference is clear and distinct between the three units referring to their accumulation curves. In conclusion, we can say that: the less water is deep in the basin, the higher the distillation rate. The total production reaches 1,808; 1,879 and 1,962 mL/m^2 for the three depths: 1.5, 1, and 0.5 cm, respectively. The gain of distilled water using 0.5 cm depth is 4.41% over than 1 cm depth and 8.52% over than 1.5 cm depth.

The photo of the three distillers during the water depth experiment is presented in Fig. 5d.

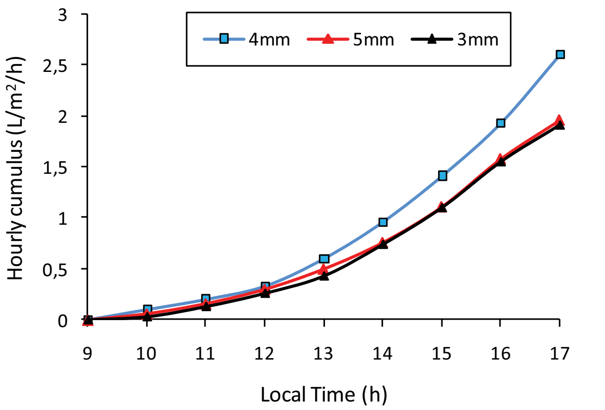

Fig. 4. Hourly cumulus vs. local time for different glass cover thickness (Feb/08/2022).

Table 2
Dimension of solar still's components

	Length (m)	Width (m)	Thickness (m)	High (m)	Area (m^2)
Basin	0.60	0.40	0.004	0.05	0.24
Glass cover	0.72	0.41	0.004	–	0.30
Insulation (polystyrene)	0.6	0.4	0.04	–	0.24

4.4. Effect of the sense of geographical orientation

The sun in the Ouargla region rises from the east and heads towards its west setting along the south.

The best position for distillers during high-intensity hours is facing towards south.

The four units are directed towards the four directions: North, South, East, and West.

All of these units receive diffuse solar intensity, which is less intense than the direct one.

The east-facing unit receives weak direct radiation at sunrise; the one facing south receives the direct highest radiation in the period between 10 a.m. and 04 p.m., while the west-facing unit receives direct weak radiation only around sunset. The unit facing north receives no direct radiation except the diffuse.

Fig. 6a presents the hourly cumulus for the different units oriented in the four geographical directions.

The amount of distillate collected up to 5:00 p.m. was: 2,087; 2,008; 1,945 and 1,491 mL/m^2 for four directions (South, East, West, and North), respectively, at the beginning of March 2022.

From this experience, we can conclude and recommend orienting the distiller facing south to benefit from the strong direct solar intensity. The gain in distilled water for the south direction compared to the north direction is almost 40%; from here we can see the importance of direct radiation compared to diffuse one.

The photo of the distillers during the orientation experiment is presented in Fig. 6b.

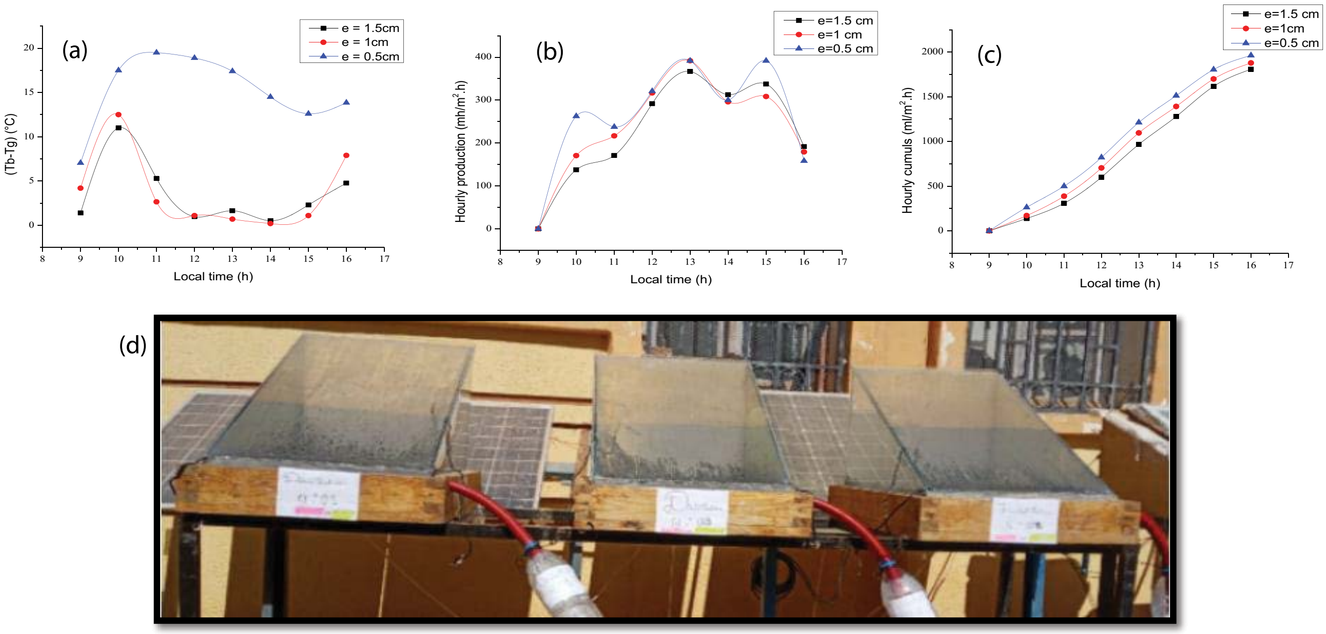

Fig. 5. (a) Temperature difference between the basin and the glass cover vs. local time (Feb/22/2022). (b) Hourly production vs. local time (Feb/22/2022). (c) Hourly cumulus vs. local time (Feb/22/2022). (d) The photo of the distillers during the water depth experiment.

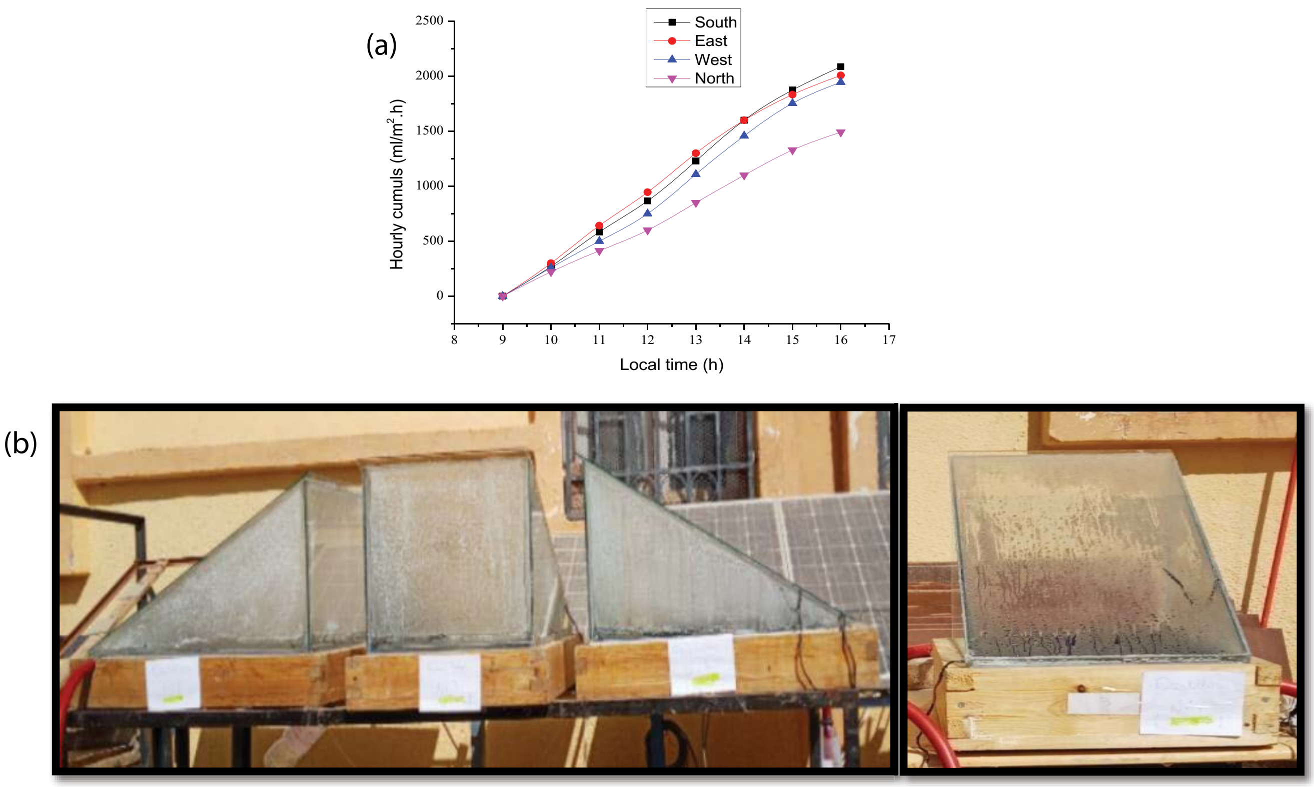

Fig. 6. (a) Hourly cumulus vs. local time (Mar/01/2022). (b) The photo of the distillers during the orientation experiment.

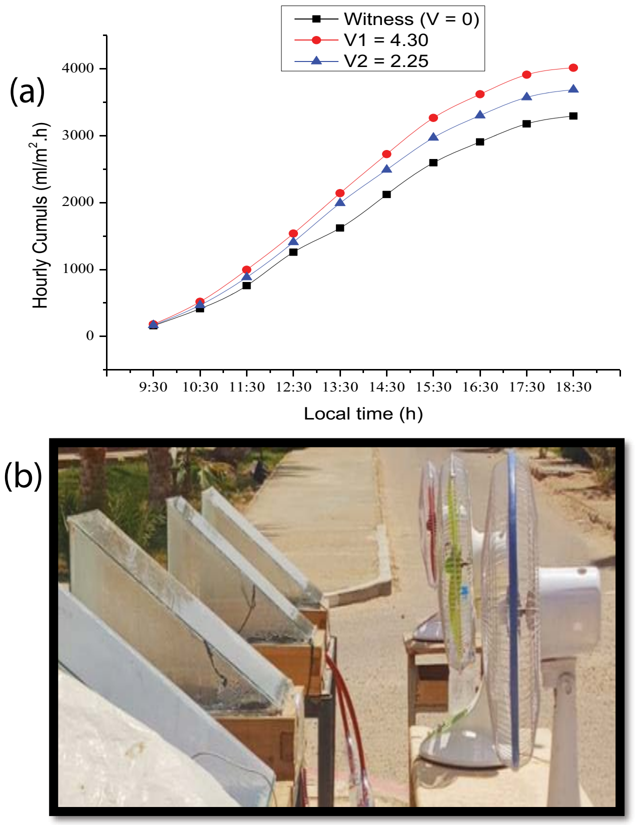

Fig. 7. (a) Hourly cumulus vs. local time for different ambient air speed (March 15th 2022). (b) The photo of the distillers with fans during the ambient air speed experiment.

4.5. Effect of the ambient air speed

Placing a fan in front of a solar still to cool the glass cover can improve its production but, on the other hand, increases the cost of the equipment and consequently increases the cost of distilled water. Our goal is only to see the effect of the air speed on the yield of the distillation to choose a suitable location for the still where the wind blows regularly. At the beginning of the experiments, we used three fans, but in the middle of the experiments, one of the fans was burnt out, and we continued our experiment using only two fans while the third still remains as a witness ($V = 0$).

According to the graphical results (Fig. 7a) it can be seen that the daily production is greater in the case of the air speed equal to 4.3 m/s.

The daily yield recorded for the three units is 3,961; 3,502 and 3,019 mL/m^2 for the air velocities of: 4.30, 2.25, and 0 m/s; hence the daily gain of the two units compared to the witness is 31.2% and 16%, respectively for air speeds of 4.30 and 2.25 m/s.

The photo of the distillers with fans during the ambient air speed experiment is presented in Fig. 7b.

4.6. Water analysis

After the experiments, certain physical parameters of the distilled and brackish water are analyzed to see the purity rate and the quality of distilled water produced.

These parameters are generally: pH, salinity and thermal conductivity.

Table 3 presents the results of these analyses.

Some organic products accompanying the water, such as phenols, can volatilize under the greenhouse effect and condense with the distilled water; which sometimes maintains high electrical conductivity; of this, the addition of certain photocatalysts or adsorbent materials is recommended to destroy and/or retain these polluting products, which make the water quality more excellent.

From the table, distillation reduced salinity by 96.3% and conductivity by 95.6%, which lets us say that the purification remains acceptable.

Table 3
Water analysis results

	pH	*T* (°C)	Salinity (ppm)	Conductivity (µs/cm)
Brackish water	6.53	23	1.08	2,109
Distillate	5.74	24	0.04	93

5. Conclusion

To answer questions from some residents of the deserted region of Ouargla concerning the design and the mode of operation of solar stills, the process engineering laboratory at the University of Ouargla has assigned this task to three Master's students who will have to answer these questions by carrying out several experiments that will lead to the manufacture of a profitable solar still.

The experiments carried out are based on the study of the effect of the thickness of the glass cover, the depth of the brackish water, the geographic direction of the still and the effect of the air speed on the performance.

The results obtained show that:

- The thickness of the glass cover is 4 mm inclined at 30° with respect to the horizon.
- The still should be placed facing south (high intensity) in a windy location (high wind speed) and working with shallow depths of brackish water (<2 cm).

The average gains acquired in relation to the parameters studied are:

- 40% for south orientation compared to the north.
- 34.38% for 4mm thickness compared to other thickness.
- 8.52% for the minimum water depth of 0.5 cm.
- 31.2% for the wind speed of 4.3 m/s.

Finally, we obtain distilled water with 96% purity and we advise users of simple solar stills to add an adsorbent or a photocatalyst to the water in the basin to get rid of all organic impurities accompanying distilled water [3,23,44].

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