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Effect of different carbon types on a traditional solar still output

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ABSTRACT

One of the biggest issues that humanity faces is access to drinking water particularly in isolated and desert regions like southern Algeria. This region is characterized by high salinity water and high solar radiation as well; so, here, solar desalination is the most appropriate solution to obtain pure water. To contribute to solving the problem, five similar solar stills were installed in aim to increase their performance by using four different types of carbon namely: activated carbon, graphite, coal and wood charcoal which they are added separately within each absorber with the same weight 100g (i.e., 0.4167 kg carbon/m^2 of absorber area). The results obtained during experiments at Ouargla University show that the various types of carbon enhance water absorption to solar irradiation. Moreover, placing carbon powder inside the fixed black cloth led to the stability of the carbon particles on the base of absorber avoiding them to float above the water, which contributed to the increase of the daily yield. Activated carbon, graphite, coal and wood charcoal improved the output by 79.39%, 57.58%, 50.30% and 18.18%, respectively relative to the baseline case.

Keywords: Activated carbon; Graphite; Coal; Wood charcoal; Absorbent materials; Solar desalination; Southern Algeria

1. Introduction

Water is the most important element that all life in nature needs to survive. Only 2.6% of the total water supply is fresh water and only 1% of this can be used by humans for a variety of purposes. Saline water accounts for 97% of total water resources [1].

Population growth that has happened rapidly in recent decades has increased pressure on water resources, which has made the situation worse [2,3].

The process of desalinating salty water to make it drinkable is a good option; thus, it is important to employ various processes such as solar distillation in order to remove salts [4,5].

The oldest known work on solar distillation was in 1551, it was done by Arab chemists [6]. Talbert et al. [7] have written a fairly thorough overview of the development, theory, uses, and solar stills' economics, it details the work carried out in several nations between 1872 and 1970. Small laboratory scaled-down representations and large installations each one is described [8].

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The solar distillation method is promising since it avoids the use of fossil fuels and employs clean energy to minimize environmental impact. It is feasible to make low cost distilled water using basic equipment when solar energy and solar stills are combined. These devices are simple to make and maintain, and their installation is advised in dry, sunny areas with abundant brackish groundwater sources when fresh water is not accessible [9,10].

The vast majority of Algeria's land is covered with solar energy during the whole year, which is a significant advantage for dry and semi-arid regions. The average solar irradiation time for Ouargla city in Algeria's southeast (latitude 31.95′ N, longitude 5.40′ E, and height 141 m) is around 3,500 h/y, giving about 2,650 kWh/(m^2·y) of solar irradiation on the horizontal surface [11].

Groundwater resources make up more than 75% of Algeria's total water supply, with a total estimated volume of 60 billion·m^3. This enormous volume of water is precious and difficult to renew. Despite its varied salinity of up to 8 g/L in certain sources, which is far beyond the permitted 550 ppm salt limits for consumption by humans, the yearly utilization approaches 5 billion·m^3 [12,13]. Therefore, it is apparent that there is a rising need for fresh water in these locations on a daily basis.

As a result, solar energy is increasingly being used to provide drinking water to remote low-density populations. According to economic calculations and conducted research, the least expensive way to manufacture drinking water is using solar distillation. As a result of the equipment's lower cost and the utilization of free energy [14]. In arid and isolated areas, the conventional solar still (CSS) has been utilized to produce clean and drinkable water from salty water. It is beneficial, straight forward, environmentally friendly, and affordable equipment [15,16].

The intensity of solar radiation, the temperature differential between the glass cover plate and the saline water, the thickness of the glass cover, the wind speed, the area of the collector, the absorption plate, the depth of the water, and the angle of inclination are only a few of the variables that influence the daily output increase [17]. The majority of scientists across the world are long studied and interested in increasing the transfer of mass and heat in the basin-type solar stills in order to decrease energy losses for enhance distiller performance [18].

The performance of traditional solar stills has been improved via several tries utilizing various techniques. A method used to produce heat generation for improvement in the productivity of traditional type solar stills is to improve the process of heat and mass transfer by adding some materials like heat storage materials, phase change materials, metal oxides (photo-catalysts), and absorption materials.

When there is insufficient sunlight, overnight, or if there is a low level of solar intensity, the using medium for strong heat is a method utilized to keep the absorber's working temperature high enough to create distillate. In solar distillation systems, some researchers have used a variety of materials for energy storage. To name a few: Portland cement, gravel, alluvial sand, rubber, sponge, bitumen, paraffin wax, and jute cloth. These materials have a high thermal storage capacity or low thermal conductivity [19].

Abdel-Rehim and Lasheen [20] employed materials such as glass, rubber, and gravel as heat storage materials. The use of the packaging layer to store thermal energy; the storage grew by 5% in May, 6% in June, and 7% in July, whereas the updated system employing a rotating shaft and photovoltaic system saw a rise of 2.5% in May, 5% in June, and 5.5% in July.

Another researcher's suggestion is to use phase change materials (PCMs) in the distillation process in order to benefit from the latent heat of phase change; this strategy feeds absorber plates with additional energy and subsequently results in excellent distillation performance [21].

By using layers of blackened alluvial sand as a heat storage medium, Sellami et al. [22] conducted an experiment. They examined how the mass of sand and the diameter of sand particles affected the production of solar still; the results showed that when using a fixed mass of sand, the productivity of the distilled water increases with the decrease in the diameter of the sand particles used. Due to the effect of the photocatalyst and the storage of heat, the production of pure water for fixed particles' diameter increases as the sand mass increases to an ideal value of 2.268 kg of sand/m^2 of absorber area; the production improves by 43.28% when compared to the baseline case. Due to the photocatalysts' presence, the distillate produced is of decent quality.

The addition of metal oxides (semiconductors) to the absorber area such as K_2O, MgO, MnO_2, TiO_2, Na_2O, ZnO, and SiO_2 allowed for certain experimental research. These semiconductors act as photocatalysts, resulting in an improvement in the production and the obtaining of water distillate of high quality. Several of these photocatalysts can also function as adsorbent materials by adsorbing and/or decomposing some organic molecules that often contaminate water [18,19,23,24].

Water has a very low rate of evaporation when exposed to solar radiation because it is a poor solar energy absorber. To enhance the conversion of photothermal energy, although the absorbance of water to solar energy can be increased after adding the absorbent materials to it [25].

Adding absorbent materials within absorber plate is a good strategy to enhance the still performance [26]. The addition of different dyes is one of the earliest suggestions for modifying solar distiller by an external material [27].

The thermal performance of a solar distillation unit was investigated by Panchal et al. [28] using a variety of various black-paint absorber materials.

The impact of coal and charcoal on the performance of solar distillers was examined by Attia et al. [29]. Both substances enhanced the thermal performance of the solar still.

While this was going on, Abdallah et al. [31] looked at how dissolved salts like copper sulphate, potassium permanganate, potassium dichromate and cobalt chloride may improve water's ability to absorb solar energy.

Experimental testing was done by Abu-Hijleh and Rababa'h [30] to determine how well a solar distiller worked with different-sized black coal and black steel cubes that were placed in the basin.

The effects of coated and uncoated metallic wiry sponges, as well as specific black pebbles, on the performance of a solar still were examined by Abdallah et al. [31]. They came to the conclusion that black rocks absorb, store and liberate heat more than sponges coated and uncoated and can increase productivity by 60%. Both absorbing materials increased the still thermal performance.

To improve distillation yields, Abd El Kawi and Naim [32] employed charcoal particles as absorber material. Due to the capillary action of the charcoal, which was partially submerged in water, as well as its dark colour and rough surface, the system's thermal inertia was decreased. In fact, the distillation process started up much faster when there was charcoal present.

To enhance the output of distilled water, Ali Ouar et al. [12] studied the effects of utilizing various absorbent materials within the basin of the solar distiller. According to their experimental findings, bitumen, charcoal, and black ink each increase the solar stills' production by 6.87%, 18.42% and 25.35%, respectively. Through the productivity of water, bitumen was the best absorbing material employed; in addition, the charcoal unit generated the best-quality water due to its role as an adsorbent and water purifier.

The ability of carbon materials to directly transform solar flux into thermal energy through the excitation-relaxation process, conjugating electrons in unsaturated bonds, prepares the ground work for their use as solar absorbers. In particular, the graphene family, carbon nanotubes, and amorphous carbon made of graphite carbon are capable of this [33].

Sharshir et al. [34] recommended employing exfoliated graphite and carbon foam with wick as a heat localization material to increase the effectiveness of solar stills. This led to a 51.8% increase in freshwater output while also raising the modified still's efficiency to 37.6%.

For uses in desalination and water treatment, activated carbon is one of the most highly sought-after materials. An evaporation rate of 1.22 kg/(m^2·h) and a photo-thermal conversion efficiency of 79.4% were observed in a recent experiment using activated carbon fibres [35].

A numerical study and modelling of a solar still was provided by Ali et al. [36]; the outcomes displayed that the addition of granular activated carbon to a solar still improved its performance.

Utilizing nanoparticles raises the temperature of the salt water in typical solar stills [37], which in turn raises coefficient of heat transfer and consequently, the evaporation rate, increasing productivity [38].

In an experiment, Sharshir et al. [39] added graphite and copper oxide micro-flakes with concentrations varying from 0.125% to 2%, in order to improve the productivity of the solar still. The water depths in the several basins ranged from 0.25 to 5 cm, and to keep condenser cool, water in various masses flows over the glass cover. According to the results obtained, the production rises by roughly 44.91% when CuO nanoparticles are used and by 53.95% when graphite microflakes are used. When using water flow over the condenser to keep it cool in the unit that contains particles of CuO and graphite, the outcome revealed that the production rises by approximately 47.80% and 57.60%, respectively. When carbon nanotubes were used in an experimental investigation by Gnanadason et al. [40] to increase the efficiency of solar distiller integrated with a vacuum pump and various water depths, the outcome was enhanced by 50%.

In light of prior research and conclusions, this experimental project's significance is in its studying the effect of using different types of carbon to increase the production of solar stills by improving the absorption of solar radiation.

In this research, we'll study the impact of utilizing activated carbon, graphite, wood charcoal and coal (brought from the remains of the mines in the Al-Qunadsa area, in south-westerner Algeria) which are covered with fixed black cloth, to improve the efficiency of traditional solar still. The tests were carried out in March 2022 at the Ouargla University in southern Algeria.

2. Methodology

2.1. Experimental set-up

Five identical solar still prototypes were created, constructed and examined, one was utilized as a conventional unit, while the others were subjected to the study's criteria. Fig. 1 displays a schematic diagram of experimental setup presently being employed in research. Each solar still has a 0.04 m thick wood construction, its basin is a plate (0.60 m × 0.040 m × 0.07 m) constructed of 0.004 m thick galvanized iron. To guarantee optimum absorption of solar irradiance and avoid any potential corrosion, the absorbers of the five solar stills were darkened with matt paint across their whole absorber area. Each assembly's foundation was also strengthened and insulated with 0.04 m thick polystyrene, which has a low thermal conductivity (0.033 W/m·K), to reduce heat loss to the outside. To improve the flow of distilled water, the stills' detachable 0.03 m thick glass lid has been angled 30° upward. The glass cover has been silicone-sealed to stop any vapor leakage.

Each still received local brackish water (2 g/L concentration) through an adjustable float to supply and keeping the still's water at the required depth. According to our prior laboratory experiments [41], the vapor rate increases when the depth is low because there is less water present, which causes its temperature to rise quickly; in our experiment, the saline water depth is set at 1 cm.

A distillate trough that runs down the bottom edge of the glass is used to collect and transfer the distillate out of the enclosure using plastic tubing.

2.2. Measuring tools

The physical characteristics of brackish and distilled water as well as meteorological factors are measured using a variety of instruments in this experiment.

- A solar-meter for measuring the solar radiation (W/m^2).
- Hygrometer to measure the ambient temperature (°C) and the relative humidity (%).
- A hot wire anemometer to measure the wind speed (m/s).
- Thermocouples K-type are used for measuring the temperature of different points of still.
- Sieves for adjusting carbon particles' diameter (mm).
- Analytical balance for measuring the different types of carbon mass (g).
- Graduated tubing to measure the volume of the distilled water produced (mL).

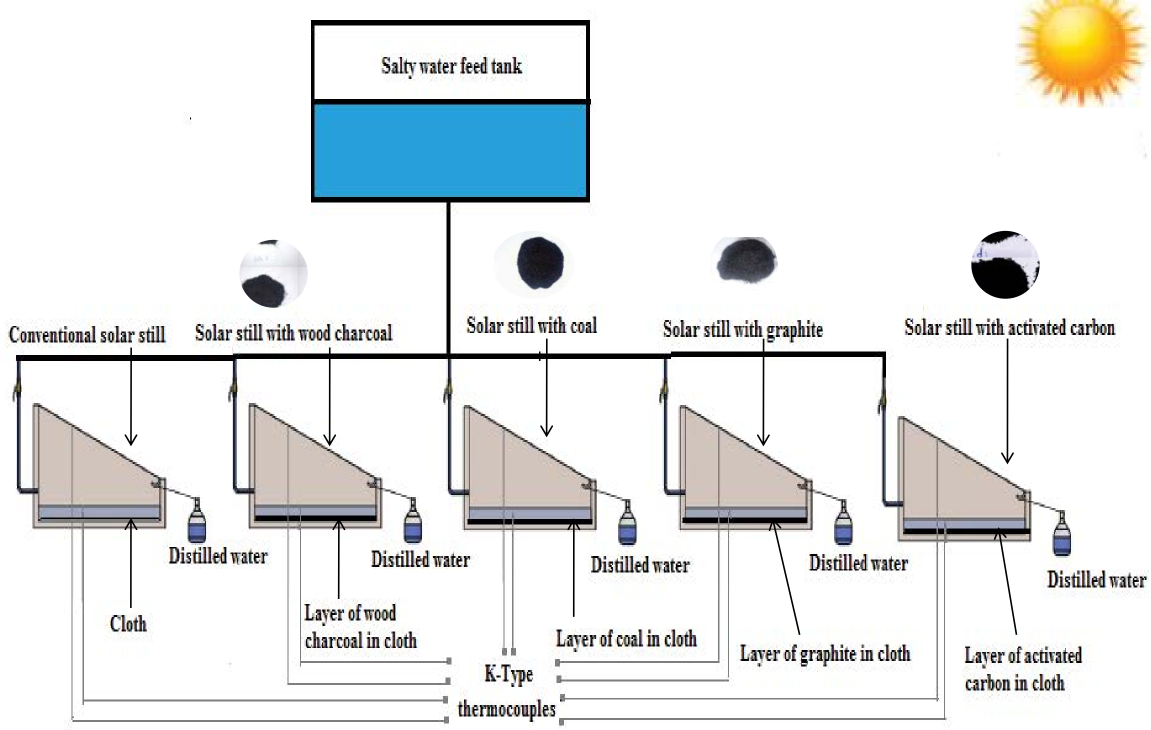

Fig. 1. Schematic diagram of experimental setup.

- Multi-parameter (Hanna – HI9829) to determine the TDS (total dissolved solids) (mg/L), electric conductivity (μs/cm), salinity (%) and the pH of water before and after the distillation.

2.3. Experimental procedure

The five solar stills were constructed and tested at Ouargla University in Process Engineering Laboratory (PEL). The stills' long axes are oriented south-north to take high solar radiation. The first solar still was used as a witness, while the four types of carbon were added separately to the other four solar stills. The different types of carbon have been placed inside the fixed black cloth, which led to the stability of the carbon particles on the base of absorber and avoiding them to float above the water. To allow a better study of the effects of carbon types and to eliminate the effect of the cloth, we fixed the same cloth in the absorber of the witness as well. In this experiment, four different types of carbon were used: activated carbon, graphite, coal, and wood charcoal separately with the same mass of 100 g of each one, (i.e., 0.4167 kg/m^2 of absorber area); this is enough to cover the entire absorber area. Particles' diameters are the same (0.080 mm); the particles should be small as possible to maximize the heat exchange area.

All tests were conducted from 9:00 AM to 5:00 PM local time. Measurements were regularly taken throughout operations to determine the temperature of the inner of glass cover and that of the brackish water in the basin. Additionally, the solar radiation, ambient temperature, wind speed, and the volume of distilled water were measured.

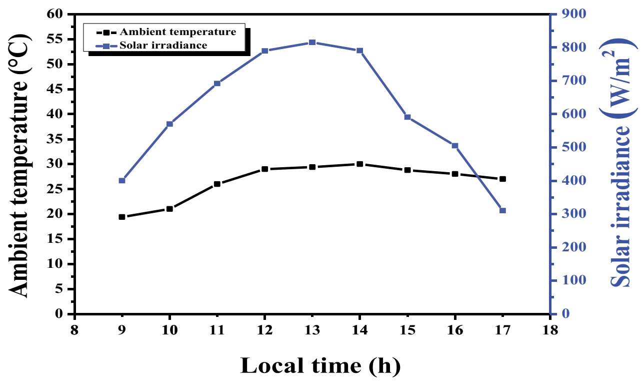

Fig. 2. Solar irradiance and ambient temperature vs. local time.

The reproducibility of the results in all experiments was confirmed by carrying out each experiment twice over the course of the following 2 d. The yield comparison between the witness and test units was used to normalize the experiment's results in the form of a productivity factor.

3. Results and discussions

3.1. Solar irradiance and ambient temperature

Fig. 2 shows solar irradiance and ambient temperature measurements vs. local time for our experiment location. During our experiments, the first half of the day sees a rise in solar irradiation, which reaches its maximum between 12:00 AM and 02:00 PM, before it starts to get low in the afternoon. At 01.00 PM local time, the maximum value that was measured was 815 W/m². The recorded ambient temperature varied between 19.4°C at 9:00 AM and 30°C at 02:00 PM.

3.2. Water and glass cover temperatures

Fig. 3a–e represents the different unit's temperatures: (brackish water temperature, the glass cover temperature and the ambient temperature) vs. local time. The majority of temperature curves in the reference still and the test stills indicate the same solar radiation-like tendency. Temperatures inside of stills are generally high due to the greenhouse effect.

Between 01:00 PM and 02:00 PM, all of the temperatures in a still reach their highest values. The highest temperature recorded for the still is the temperature of the brackish water (T_w), since the solar radiation is absorbed in the basin, the water temperature in the basin was the highest. This was followed by the glass cover temperature and then by the lowest ambient temperature.

The highest of brackish water temperature ever recorded was 62.5°C at 02:00 PM, in the solar still unit containing activated carbon. The average glass-cover temperature (T_g) measured for the activated carbon unit, the graphite unit, the coal unit, the wood charcoal unit and the reference unit

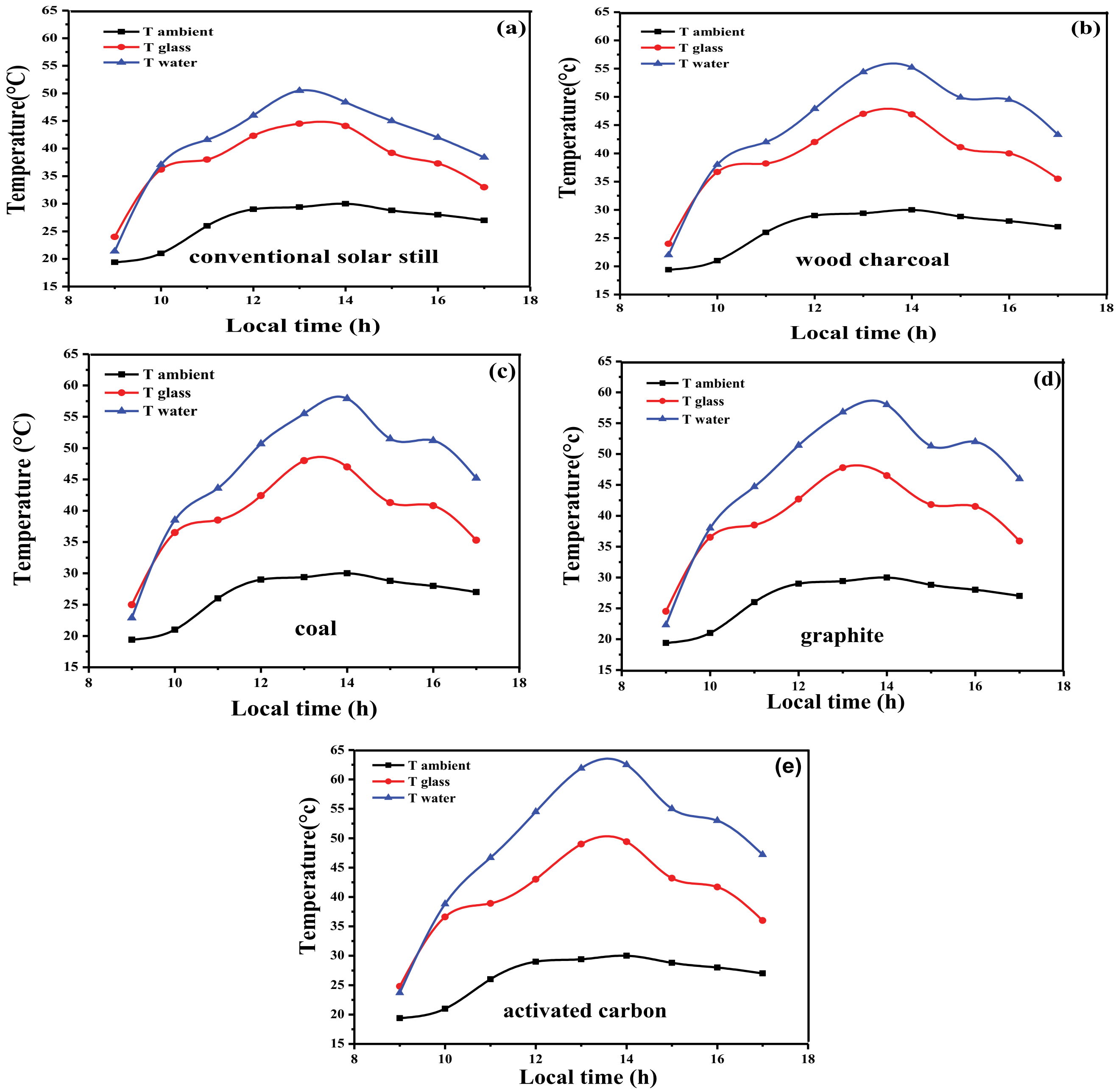

Fig. 3. Different temperatures for (a): conventional solar still, (b): wood charcoal unit, (c): coal unit, (d): graphite unit and (e): activated carbon unit.

are 40.28°C, 39.5°C, 39.42°C, 39.04°C and 37.62°C, respectively. These temperatures represent how much vapour condensation heat is present, which its condensation raises the temperature of the inner surface of the glass cover. In general, we can see that the temperature of the water in the basin (T_w) is higher than that of the condenser (the inner surface of glass cover: T_g) for all experiments. The quantity of the distilled water obtained is generally reflected by the value of the gap between them.

3.3. Temperature difference between the water in the basin and the glass cover

Fig. 4. displays the temperature difference between the water in the basin (T_w) and the condenser (T_g) for the five stills. Generally, the temperature of water in the basin (T_w) should be higher than the condenser temperature (T_g) for distillation to occur. The difference between them is a direct reflection of the volume of distilled water. For the unit with activated carbon this gap recorded is 8.96°C at 02:00 PM; the maximum value was recorded is 13.1°C. For the conventional unit, the rate value of the gap is 3.53°C and the maximum value recorded is 6°C at 01:00 PM local time.

What is surprising is that the gap for all stills was negative ($T_g > T_w$) at the beginning of the experiment; this could be accounted for by the fact that, before 9:00 AM, the sun's rays strike the glass cover first before reaching the water in the basin; which, due to thermal inertia, water still retains the low temperature of the last night; it is for this reason that we observe that the temperature of the glass is slightly higher than that of the water, which makes the difference negative; this phenomenon will not be observed later.

3.4. Hourly yield

Fig. 5 displays the five stills' hourly production vs. local time. According to the curves' tendency, the hourly production is directly related to solar irradiance. Between 12:00 AM and 02:00 PM local time, the maximum values were obtained.

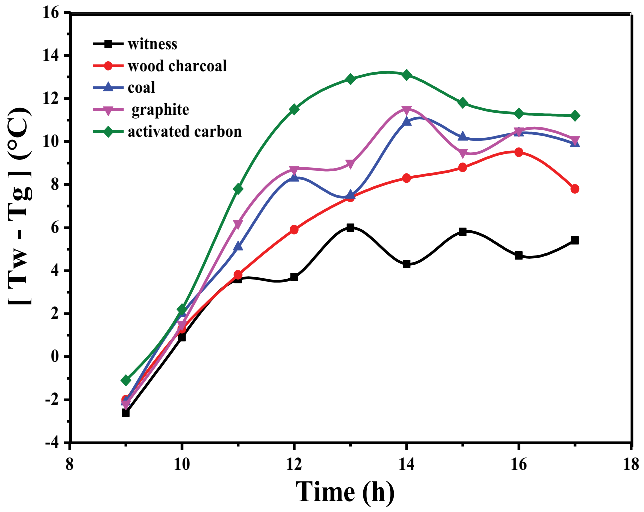

Fig. 4. Temperature difference between the water in the basin and the condenser for all units vs. local time.

At the end of the trial, each unit's mean hourly productivity was computed as follows: 0.3690, 0.3239, 0.3097, 0.2243, and 0.2062 L/m^2·h for the units with activated carbon, graphite, coal, wood charcoal and the reference unit, respectively.

The best unit was the one that contained activated carbon. This was explained by the dual function of the activated carbon; firstly, as a heat-absorbing medium; secondly, it has a high porous structure compared with other types of carbon, which provides more surface area; this character improves the evaporation rate. Additionally, it is evident that graphite also offers well-performing due to its high thermal conductivity value of (139 W/m/K) in comparison to other types of carbon. In general, brackish water's temperature and mass and heat transfer coefficients increase under high irradiance, which help us to explain the increase in the output.

3.5. Daily yield

Fig. 6 displays the daily yield of distillate for all units; the modified solar stills have more total distillate at the ending of the experiments than the witness recorded. The presence of different types of carbon and their effects are what have caused the output of distillate to improve. The cumulus for all units is: 2.96, 2.60, 2.48, 1.95 and 1.65 L/m^2·d produced by various types of carbon units: activated carbon, graphite, coal, wood charcoal and the conventional still. Finally, the productivities of the modified unit are enhanced by, respectively, 79.39%, 57.58%, 50.30% and 18.18% compared to the baseline case.

4. Water analysis results

We evaluated salinity, pH, total dissolved solids (TDS), and electrical conductivity as a means of assessing the quality of brackish and distilled water (with and without different types of carbon). The results of these analyses are summarized in Table 1.

This analysis indicates that the addition of different carbon types not only increases still production but also enhances the quality of distilled water due to porous structure of carbon and other physicochemical properties which lead to the adsorption of organic and inorganic pollutants.

The distilled water produced by the unit containing activated carbon was of the highest quality. This is because

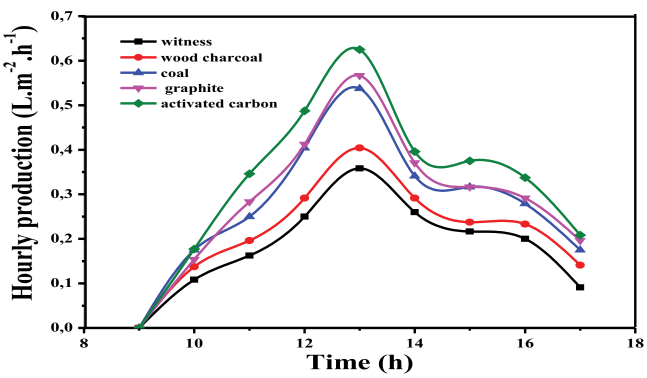

Fig. 5. The hourly yield for all units vs. local time.

Table 1
Outcome of the water analysis

Quality of water	Salinity (%)	Conductivity (µs/cm)	TDS (mg/L)	pH
Brackish water	1.6	3,165	1,586	8.07
Distilled water (witness)	0.02	35	17	6.92
Distilled water (wood charcoal)	0.02	49	25	6.8
Distilled water (coal)	0.02	34	17	7.06
Distilled water (graphite)	0.01	35	19	6.51
Distilled water (activated carbon)	0.01	16	8	6.6

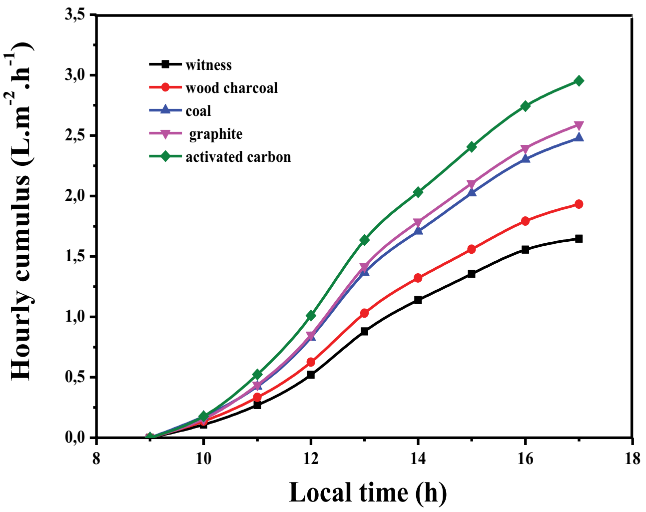

Fig. 6. Hourly cumulus (daily yield) for each studied unit.

activated carbon is basically used for water treatment applications.

According to those analyses, the distilled water quality complies with WHO's permissible value [42].

5. Conclusion

The scarcity of potable water in isolated, arid and desert regions of southeast Algeria has now become a serious concern. People who live there use groundwater that is available but frequently too salty for human consumption. One of the least expensive solutions is solar distillation utilizing conventional solar stills given the region's year-round high levels of solar irradiation and the low cost of these devices.

The aim of this experimental study is to enhance the performance of a solar still by using the effect of four different types of carbon, namely: activated carbon, graphite, coal and wood charcoal, which are added separately with the same amount within each absorber of the solar still under the climatic circumstances of Ouargla city.

According to the performance of the solar stills, the following conclusions can be obtained:

- The performance of the solar still was improved by using different types of carbon, which raised water absorption for solar radiation and increasing the temperature of the water inside the distiller.
- The carbon powder helped to improve the rate of evaporation by enlarging the exchange area.
- Activated carbon is one such material with desirable absorption properties for the application of solar distillation which has highly porous structure increases the coefficient of heat transfer and excellent solar absorption behavior.
- The addition of 100 g of each of activated carbon, graphite, coal and wood charcoal separately within the absorbers of the four separate units increases the solar still's production by: 79.39%, 57.58%, 50.30% and 18.18%, respectively relative to the witness.
- The idea of putting carbon powder inside a fixed black cloth on the absorber surface is recommended in the process of solar distillation because it contributes to the stability of the carbon particles on the absorber surface, which allows the water to absorb the maximum solar rays, resulting in an increase in the productivity of distilled water.
- The physical analysis shows that using different types of carbon as absorbent materials produces distilled water of high quality.

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