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Experimental study to improve the performance of a conventional single-slope solar still using the photo-catalytic effect of three different metal oxides

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ABSTRACT

Drinkable fresh water is essential for life on earth. Getting potable water is one of the major problems facing humanity in many parts of the world especially in remote and arid zones as southern Algeria. Nowadays, the best non-conventional method and environmentally friendly manner to purify brackish or sea waters is the solar distillation. This experimental work aims to improve the yield of conventional single-slope solar still with by providing units separately by different metal oxides namely: copper oxide (CuO), iron oxide (Fe_2O_3), and zinc oxide (ZnO) with different weight concentrations (0.04%, 0.08%, 0.12%, and 0.16%). Experimental results carried out at Ouargla University reveal that those metal oxides play the role of photo-catalysts whatever their concentrations. The productivity of test stills increases by 22.43%, 16.64%, and 13.02%, respectively for CuO, Fe_2O_3, and ZnO compared with the conventional still for a weight concentration of 0.16% of metal oxide and 1 cm of brackish water depth. After physical analysis, the distillate produced by the three units is high quality compared with that produced without metal oxides' presence. The estimated cost of 1 kg of distillate is respectively: 0.0090, 0.0089, and 0.0096$ compared with 0.0092$ in the baseline case.

Keywords: Solar still; Metal oxide; Photocatalyst; Brackish water; Southern Algeria

1. Introduction

Water is a blessing from God and a prerequisite for the continuation of life [1,2]. The water covers about 70% of the earth's surface; more than 97% of the water is saline or brackish. Freshwater consists of less than 3% of which 1% is within human reach and 2% remains frozen [3,4]. In recent times, with population increase, water consumption increases dramatically where it exceeding the limits of available water resources by cause of overexploitation and environmental pollution especially in the North African and Middle East countries [5]. One of the solutions to convert brackish and saline water to drinkable freshwater is the use of solar stills. In the still, the brackish water is heated after absorbing solar energy and evaporates then condenses on the inner glass cover face [6]. First solar desalination application was in 1872 at Las Salinas in Chile. Carlos Wilson, a Swedish engineer supplied drinkable water to workers at a salt peter and silver mine by the process converting saline water to potable water. Solar still is simple in design and construction and requires no low costs and maintenance; its important advantage is the use of solar energy instead of fossil fuels [7,8].

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Solar stills can be classified into two categories: passive and active. The passive stills receive direct solar radiation as a source of energy while in active stills; additional heat is supplied to the still from auxiliary equipment [9]. Solar stills are used in some arid or remote areas, such as the south of Algeria [10], in the northwest region of China [11], and the rural districts in India [12], where low freshwater sources and where solar energy is available. Those devices were plenty used worldwide but their disadvantage is their low productivity. Many investigations studying different key parameters and carried out works in order to improve the performance of solar stills such as free surface area of water, glass cover angle, depth of water, energy storing materials, etc. [13,14].

Recently, researchers used different designs of solar stills namely: single slope solar still (SSSS) [15], double slope solar still [16], double-basin [17], triple-basin still [18], greenhouse type solar still with mirrors [19], pyramid solar still, spherical, and hemispherical solar still [20], tubular solar still [21], triangular pyramid [22], inverted absorber solar still [23].

A lot of researchers, carried out studies on different theoretical and experimental methods to increase the production rate and enhance the efficiency of solar stills by adding heat-absorbing materials to increase evaporation of brackish water or adding external equipment such as coupling a flat-plate collector with solar still [24], plastic/compact heat exchangers [25], water sprinkler [26], heaters [27], absorption heat pumps [28], external solar collector [29], phase change materials [30], mixture of Portland cement and alluvial sand [31], Portland cement[32], blackened layers of sponge [33], black rubber and black gravel [34,35], Bitumen, charcoal, and black ink [36].

In the near past, with the development of nano-materials, nano-fluids have attracted the attention of many investigators and researchers in solar energy [37–40]. The first use of nano-fluid is by Choi in 1995 in aim to increase the thermal conductivity of fluids at the Argonne National Laboratory in USA [41]. The nano-fluids are some fluids containing nano-particles normally with size from 1 to 100 nm. Researchers have used certain types of nano-particles such as metal oxides, carbon nano-tubes, metal carbides, nitrides, metals nitrides, and nano-tubes as colloidal suspensions within a base fluid such as water, ethylene/propylene glycol, oils, and other lubricants [42–45]. In recent times, some investigators have to add nano-fluids in the solar still to increase the productivity of distilled water.

Gnanadason et al. [46] conducted an experimental study to enhance the productivity of SSSS integrated with a vacuum pump and different water depths using carbon nano-tubes, the result was improved by 50%.

Kabeel et al. [47] investigated experimentally the effect of using aluminum oxide, vacuum fan, and outside condenser to the active solar still. They concluded that the productivity increased by 53.2% when using the outside condenser while an increase by 116% is found was adding Al_2O_3 nano-particles.

Elango et al. [48] conducted an experimental study using an SSSS with different nano-fluids (Al_2O_3), (SnO_2), and (ZnO) with a saline water depth of 1 cm. The enhancement of daily productivity is about 30%, 19%, and 13% for aluminum oxide (Al_2O_3), tin oxide (SnO_2), and zinc oxide (ZnO), respectively.

Sahota and Tiwari [49] studied experimentally and theoretically the performance of a double slope solar still (DSSS) adding alumina oxide Al_2O_3 with various concentrations. The productivity was improved by 12.2% and 8.4% at 35 and 80 kg for fluids masses, respectively.

Sharshir et al. [50] carried out an experimental study in aim to increase the productivity of the solar still by adding graphite and copper oxide micro-flakes with different concentrations from 0.125% to 2%, and different basin water depths ranged from 0.25 to 5 cm, and different cooling water mass flow over the glass cover. The results showed that the yield increases by about 44.91% with copper oxide nanoparticles and 53.95% with graphite micro-flakes. In the case of using the cooling water flow over the glass cover with copper oxide and graphite particles, the result showed that the yield increases by about 47.80% and 57.60%, respectively.

Gupta et al. [51] fabricated an SSSS with white painted side walls. They performed experiments by adding nanoparticles of copper oxides (CuO) with a mass concentration of 0.12% and different water depths (5–10 cm); they found that a daily enhancement in the productivity is about 47.80% and 57.60%, respectively.

Photocatalysis technique has been attracting much research interest because of its wide applications in solar energy and environmental remediation [52–54]. The photo-catalysis phenomenon is the absorption of a photon whose energy is greater than the gap between the valence and the conduction bands of the semiconductor. After this absorption, a pair (electron–hole) is formed on the surface of the photo-catalyst after the emission of an electron in the conduction band and the formation of a hole in the valence band. In the presence of H_2O and O_2, this pair (electron–hole) generates the formation of free radicals which initiate red-ox reactions in the molecules of compound adsorbed on the surface of the semiconductor and causes its degradation with energy release. Due to their high red-ox potential, electrons, and photo-generated holes degrade almost all types of organic, inorganic (microbial contaminants) present in water, which explains the improved quality of distillate [36].

The present work shows a study of solar distillation with photocatalysis' effect for remote and arid areas in Ouargla southeast of Algeria (latitude 31.95 north, longitude 5.40 east, and altitude 141 m above the sea level) these area are blessed with huge underground water resources estimated at about 60 × 103 billion m^3 or approximately 76% of Algerian groundwater reserves.

This region is characterized by a water salinity of 2–8 g/L in most places and high solar intensity which is estimated at some 3,450 h/y, delivering around 2,700 kWh/ (m^2 y) of solar irradiance on the horizontal surface with long duration of daily sunshine and high ambient temperature [36,55,56].

Four single basin SSSSs were set up at Ouargla University were the experiments were conducted in order to compare the still performance with and without photocatalyst. Solar stills operate in the same location and climate conditions simultaneously. Three photo-catalysts of different metals with different concentrations were added.

2. Experimental setup

2.1. Construction of solar stills

In this experimental work, four prototypes of SSSS were fabricated; one of them was used as a conventional solar still, while different metal oxides (photo-catalysts) were added to the three others. The four units were operating under the same meteorological parameters, namely: ambient temperature, solar radiation, and wind velocity. The distillers used in our experiments have the same dimensions, each distiller consists of a wooden support as insulation, it has a thickness of 0.04 m; its basin is a tray with the following dimensions: (0.05 m × 0.40 m × 0.60 m), made of galvanized metal 0.003 m thick. Absorbers of all stills were blackened to ensure maximum absorption of solar rays. The base of each assembly was further lagged with a 0.03m thick polystyrene insulation. Removable tilted glass cover of the stills was placed to carry out distilled water, it has the following dimensions: 0.41 m × 0.61 m, its thickness is 0.003 m; it is inclined with respect to the horizon with an angle of 30°. The glass cover was sealed by silicone to prevent any vapor leakage. Underground brackish water (2 g/L) was supplied to each unit from storage tank via an adjustable float to maintain the desired brackish water level in the still (L) at $0.005 \text{ m} \le L \le 0.010 \text{ m}$ according to our previous laboratory experiences [31,32,33,36], when the depth is low the amount of water is also low so its temperature increases rapidly and hence, the vapor rate enhances. For heat and mass transfer effectiveness, brackish water level in our study is fixed at 1 cm. Distilled water is collected out of the distiller through plastic tubing Fig. 1.

2.2. Experimental procedure and measurement

The four solar stills were installed and examined in the Process Engineering Laboratory (PEL) at Ouargla University, south of Algeria, with long axes of the stills facing south-north direction in order to take in high solar irradiance. Firstly, in order to find the best yield, we tested the four basin stills with different depths of water: 1, 2, 3, and 4 cm; after the preliminary tests, the optimal brackish water depth is 1 cm. The first solar still remains the conventional unit, while the others operated with adding separately 3 metal oxides available with low quantity in our laboratory, namely: copper oxide (CuO), zinc oxide (ZnO), iron oxide (Fe_2O_3), and with different mass concentrations (0.04%, 0.08%, 0.12%, and 0.16%). The specifications of metal oxides are shown in Table 1.

All experiments started at 9:00 a.m. and ended at 6:00 p.m. local time. During operations, measurements of temperatures of glass cover inner surface, the temperature of the trapped steam inside the still were done; also, basin temperature and the temperature of brackish water were regularly measured by using type K thermocouples associated with National Instruments acquisition box. With this module, we can add thermocouples to mixed signal test systems to offer high-performance data acquisition on PC with NI-Signal Express Software.

Fig. 1. Photograph of the experimental setup.

Table 1
Specifications of photo-catalysts

Name and symbol	Density (g/m^3)	Purity (%)	Particle size (nm)	Color	Molecular weight (g/mol)	Thermal conductivity W/(m K)
(CuO)	6.4	>99.9	40	Black	79.55	76
(Fe_2O_3)	5.242	>99.9	30	Red–brown	159.69	7
(ZnO)	5.607	>99.9	30	White	81.38	29

The ambient temperature, solar irradiance, and wind speed were measured by a pyrometer with an integrator (Kipp and Zonen B.V, pyrometer model CMP 3). Distilled water volume was also monitored. The reproducibility of the results in all tests was ascertained by repeating each experiment two times in two subsequent days. The results of each experimental series were normalized, in a form of productivity factor, which simply the yield comparison between the witness and the test units.

3. Results and discussions

As shown, Fig. 2 displays measured ambient temperature and solar intensity vs. local time for our experiment location (24/04/2018). During our experiments, ambient temperature monitored was between 24°C at 9:00 h and 41.19°C at 14:00 h; solar intensity increases in the first half of the day and reaches its maximum value between 12:00 and 14:00, before it starts to decrease gradually in the afternoon. The maximum value recorded was 991.24 W/m² at 13:00 h local time.

Fig. 3 shows the variation of the solar radiation and ambient temperatures vs. local time monitored during 06 different days (from 24/04/2018 to 02/05/2018). It is observed that the temperature follows the same trend as the solar irradiance; it increases gradually in the first half of the day and decreases after it. Maximum values are recorded generally between 13:00 and 15:00.

In what follows, Figs. 4 and 5, we will only present the best case with a concentration of 0.16%. The other results less important for the concentrations of 0.04%, 0.08%, and 0.12% will not be shown; so, as not to disturb the reader by presenting the most important and the essential results only.

Fig. 4 shows the hourly productivity for all experiments vs. local time. The curves trend indicates that the hourly yield is directly proportional to the solar irradiance because of the photo-catalytic effect of metal oxides. Generally, under high irradiance, the heat and mass transfer coefficients of brackish water enhance because they are related to temperature what leads us to explain the rise in productivity.

The maximum values were recorded between 13:00 and 15:00 h local time.

The mean value of hourly production recorded at the end of experiments for each unit was: 0.525, 0.508, 0.504, and 0.458 kg/m²/h for the units with copper oxide (CuO), iron oxide (Fe_2O_3), zinc oxide (ZnO), and with a concentration of 0.16% and the conventional solar still, respectively. The solar still with copper oxide was shown as the best in terms of productivity, maybe it is due to the high thermal conductivity of copper oxide. The daily yield (hourly cumulus) which will be shown later in Fig. 5 will give a clear idea about the production rate for these four solar distillation's units.

Fig. 5 displays the daily yield of distillate for all units. At the end of experiments, the modified solar stills have a quantity of total distillate more than that of the witness. The increase in distillate's production is due to the existence of photo-catalysts and their effect. The cumulus for all units are: 3.53, 3.36, 3.25, and 2.88 kg/m²/d produced by various photo-catalysts units: copper oxide, iron oxide,

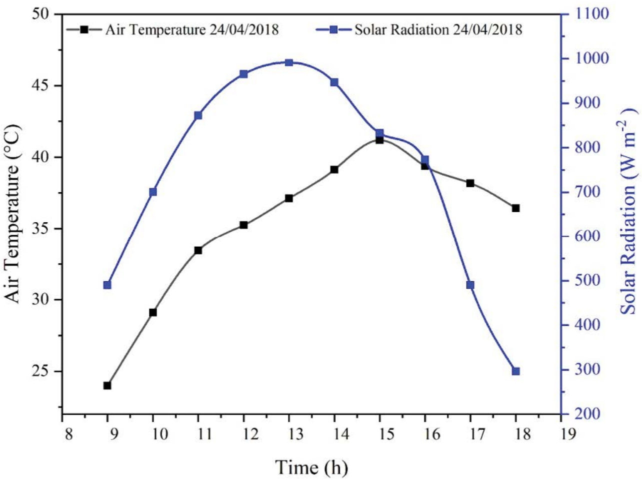

Fig. 2. Ambient temperature and solar irradiance vs. local time.

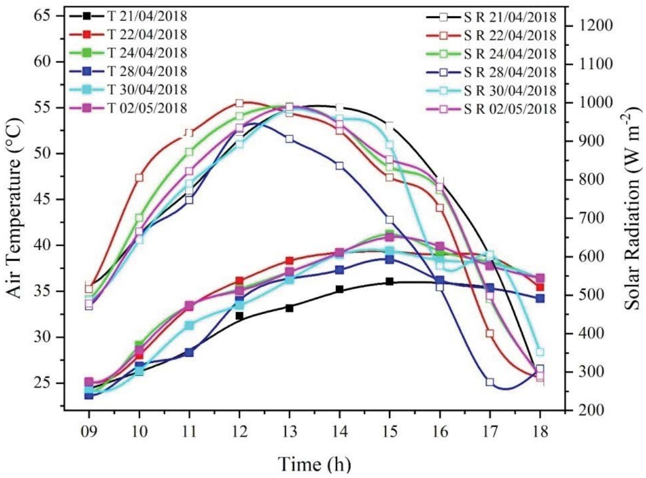

Fig. 3. External air temperature and solar irradiance during a week.

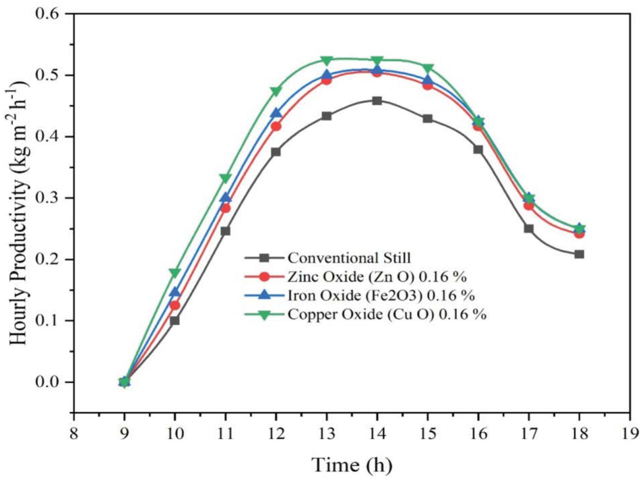

Fig. 4. Hourly production vs. local time for all units.

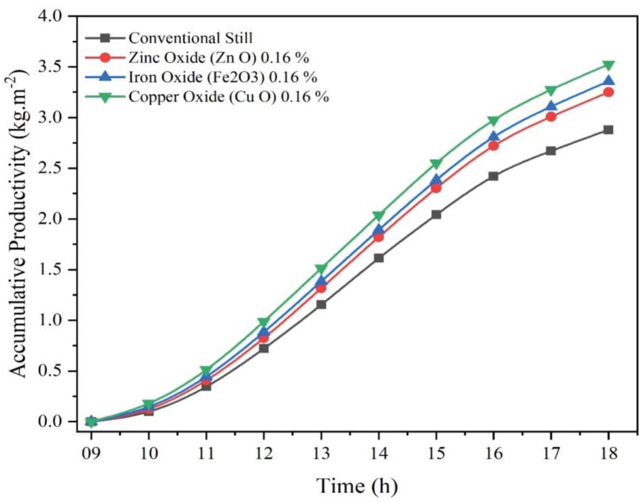

Fig. 5. Yield of distillate for all units under study.

zinc oxide, and with a concentration of 0.16% and the conventional still, respectively. Finally, the active unit's productivities are increased by about: 22.43%, 16.64%, and 13.02%, respectively compared with the baseline case.

Figs. 6a–d display the various unit's temperatures (temperatures of the Basin, the temperature of brackish water, the temperature of the trapped steam inside the still, and that of the glass cover) vs. local time with 0.16% concentration of different photo-catalysts. Almost all temperature's curves in all of stills (conventional and test stills) follow the same trend as the solar intensity. All of still's temperatures reach their maximum values at 14:00 h. The highest temperature recorded for the still is that of the mixed vapor and air trapped inside the still (T_{vapor}), because of the greenhouse effect and the overheating caused by the latent heat of vapor's condensation. The maximum value recorded for this temperature was 69.30°C in the still provided by copper oxide (CuO). The temperature of the Basin and that of the water within it are almost identical for all

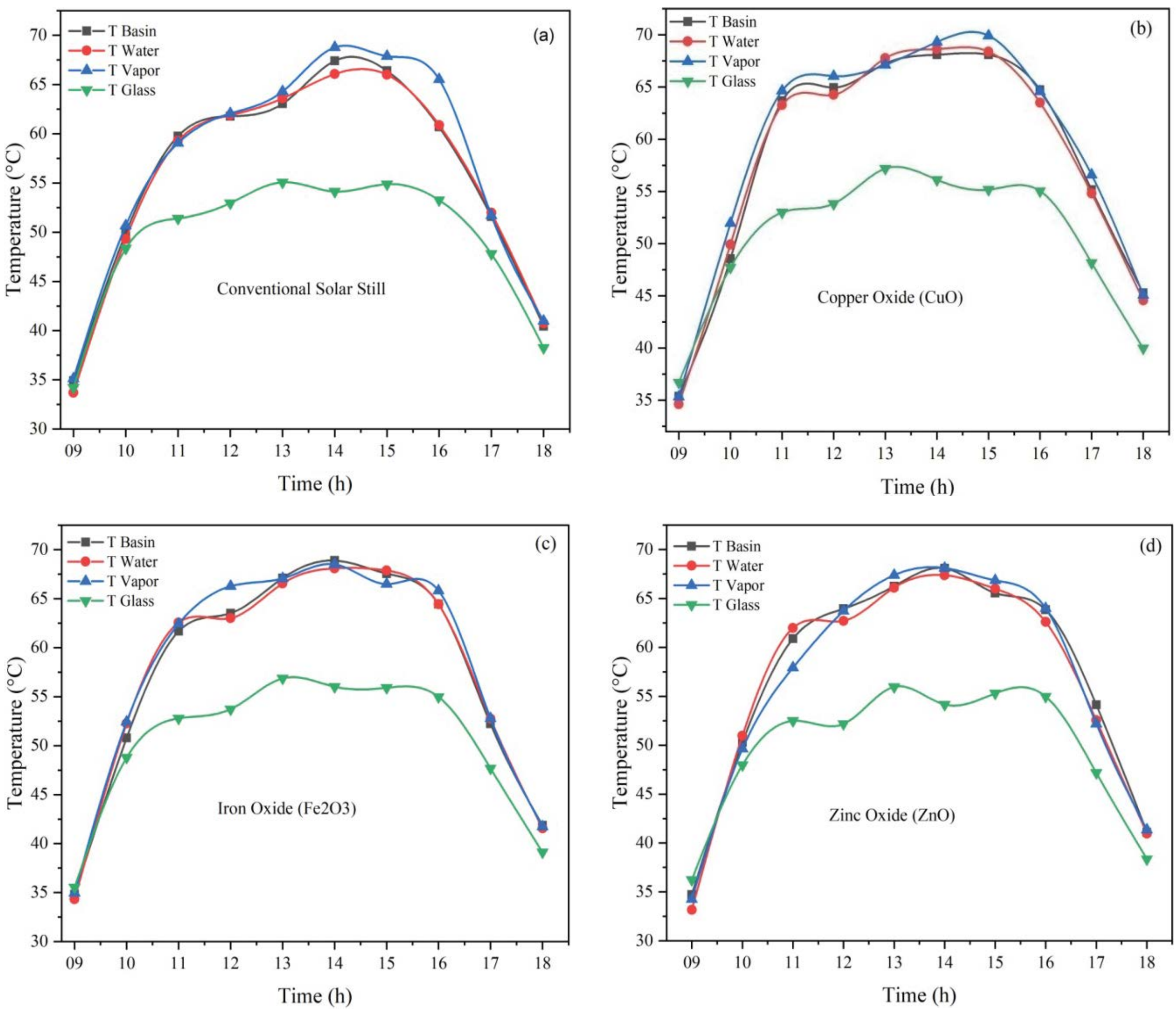

Fig. 6. Different temperatures for (a) witness still, (b) CuO unit, (c) Fe_2O_3 unit, and (d) ZnO unit.

experiments with negligible difference (about 01.00°C) due to the convective heat transfer between the base and brackish water.

So, in this case, we can write $T_w \approx T_{abs}$.

Generally, for all experiments, we can observe that the glass-cover (condenser)'s temperature (T_g) is lower than that of brackish water (T_w), the difference between them reflects directly the amount of the condensed vapor or otherwise, the amount of distilled water.

Fig. 7 shows the difference between water temperature (T_w) and glass-cover temperatures (T_g) vs. local time for all stills (conventional and test tills). This difference is directly proportional to the quantity of distilled water. It's obvious that the maximum values of the temperature difference recorded between 14:00 and 15:00 h when the solar irradiance is high; for all units with copper oxide, iron oxide, zinc oxide, and the conventional still, those differences are the follow 13.23°C, 12.09°C, 11.21°C, and 11.11°C, respectively.

As we can notice at the start of all experiments, the temperature gap for all stills is negative ($T_g > T_w$); this was explained by the fact that in the morning-time after sunrise, the glass-cover is begin to receive solar rays before the brackish water which is still cold because it's still keeping night temperature because of thermal inertia; so, the glass-cover temperature become slightly higher and therefore, the difference was shown negative.

Fig. 8 shows the effect of different concentration of photo-catalysts on the productivity. It is illustrated that the output enhances when increasing the metal oxide concentration. First, between 0.04% and 0.12% of photo-catalyst concentration, the increase of productivity is rapid, but between 0.12% and 0.16%, the enhancement percentage in the productivity is show slow. Finally, we can summarize that the productivity increases when increasing the photo-catalyst concentration. Our experiments were stopped at 0.16% because of the lack of chemical products.

4. Water analysis results

In order to determine the quality of brackish and distilled water (with and without photo-catalyst), we analyzed some of their parameters namely: salinity, pH, total dissolved solids (TDS), and electrical conductivity. Table 2 summarizes the values of these analyzes. Those analyses show that not only the adding of photo-catalysts enhances the still production, but also it improves the quality of distilled water because of the photo-catalyst behavior of these metal oxides. From those results, it was found that the distilled water quality lies in the acceptable range according to WHO [57].

5. Cost of distilled water

The cost of each distiller part is estimated in Algerian Dinars currency (DZD) and converted to US$ using the conversion (1 US \$ ≈ 119 DZD). The cost of an ameliorated unit includes the cost of conventional still added to the cost of photo-catalyst used. The cost estimation for various components used in the present basin solar still is given in Table 3. The fixed cost of the witness still is about F_C = 64\$. Assume

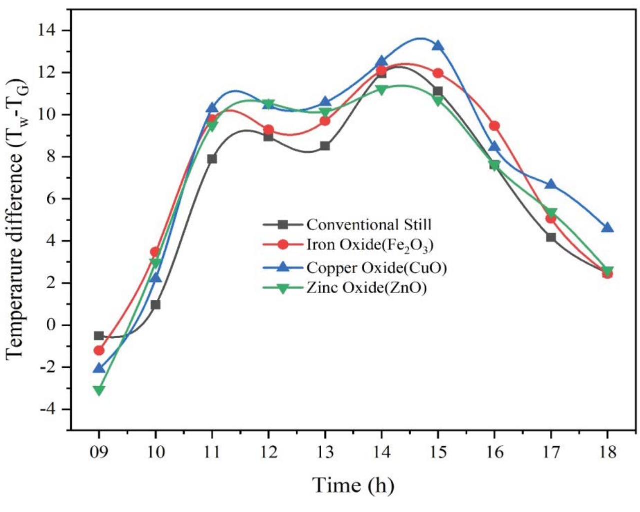

Fig. 7. (T_w – T_g) for all units.

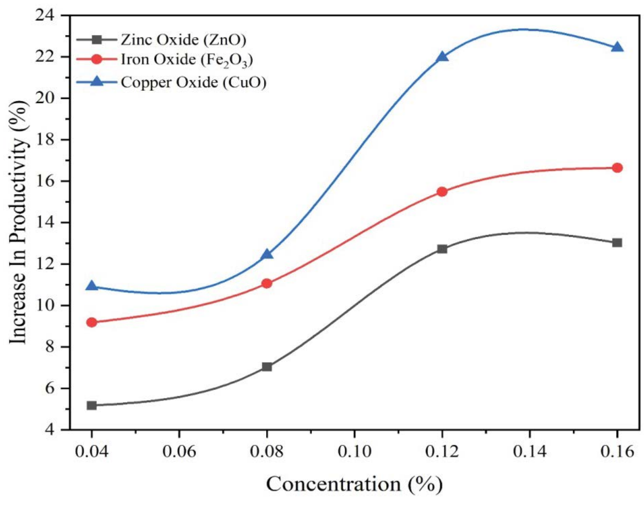

Fig. 8. Concentration effect on productivity.

Table.2
Results of water analysis

Water quality	Salinity (%)	Conductivity (µs/cm)	TDS (mg/L)	pH
Brackish water	01.932	2,865	1,940	8.20
Distilled water without photo-catalysts	00.04	02.35	6.01	6.97
Distilled water with photo-catalysts' presence	00.01	02.22	4.13	6.88

Table.3
Costs of all units with (US$) currency

Material	Cost of witness still	Cost of the still with CuO	Cost of the still with Fe_2O_3	Cost of the still with ZnO
Construction of solar still	48	48	48	48
Ducts and flask	11	11	11	11
Paints and silicon	5	5	5	5
Photo-catalyst	–	13	09	11
Total costs (F_c)	64	77	72	75

variable costs V_C equal 0.1 F_C/y, and T_C is the total cost, where: $T_C = (F_C + V_C)$ and for the expected still life (20 y), the $T_C = (64 + 0.1 \times 64 \times 20) = 192\$$.
Where the daily productivity can be estimated from the analyses of different experiments, and it is about 2.88 L/m/d, the still operates 360 d in the year, where the sun rise along the year in Ouargla Algeria.

The total yield during the witness still's life = (2.88 × 20 × 360) = 20,736 L.

The cost of 1 L of distilled water produced by the witness still is 192/20,736 = 0.0092$.

In addition,

The cost of 1 L of distilled water produced by the still with (CuO) is (77 + 0.1 × 77 × 20)/(3.53 × 20 × 360) = 0.0090$.

The cost of 1 L of distilled water produced by the still with (Fe_2O_3) = (72 + 0.1 × 72 × 20)/(3.36 × 20 × 360) = 0.0089$.

The cost of 1 L of distilled water produced by the still with (ZnO) is: (75 + 0.1 × 75 × 20)/(3.25 × 20 × 360) = 0.0096$.

6. Conclusion

Our aim in this experimental investigation is to improve the performance of an SSSS under the separately photo-catalytic's effect of three different metal oxides namely: CuO, Fe_2O_3, and ZnO under the climate conditions of Ouargla City.

On the basis of results obtained, we can conclude the following points:

- It was found that the geographical location may have a significant positive effect on the increased distilled water productivity especially for those locations with an abundant solar irradiation and brackish groundwater's reserve such as southern Algeria.
- The increase in distillate production is also due to the existence of photo-catalysts. This result shows the importance of the high thermal conductivity that is characterized by them.
- The optimal weight concentration when using the copper oxide, iron oxide and zinc oxide, at different concentrations (0.04%, 0.08%, 0.12%, and 0.16%) is close to 0.16%.
- The maximum increase in daily productivity recorded with units provided by copper oxide (CuO), iron oxide (Fe_2O_3), zinc oxide (ZnO) is 22.43%, 16.64%, and 13.02%, respectively, compared with the baseline case.
- Through water analyses done before and after distillation for several physical parameters namely: TDS, pH, salinity, and electrical conductivity, those physical parameters show that not only the added photo-catalysts enhance the still production, but also enhance the water quality because of their adsorbent's behavior.
- After an economic calculation, the estimated cost of 1 kg of distillate is about 0.0090, 0.0089, and 0.0096$ when providing the unit with copper oxide (CuO), zinc oxide (ZnO), and iron oxide (Fe_2O_3), respectively, compared with 0.0092$ in the case of the witness still.

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