Desalination and Water Treatment
www.deswater.com

doi: 10.5004/dwt.2021.27364

229 (2021) 1–9
July

Experimental study of solar water distiller integrated with solar chimney

M.E. Ali Ouar, M.H. Sellami*, S.E. Meddour, O.B. Mokrani

Process Engineering Laboratory, Department of Process Engineering, University of Kasdi Merbah Ouargla, Ouargla, Algeria, Tel. +213 771168857; Fax: +213 29 711975; email: sellami2000dz@gmail.com (M.H. Sellami), Tel. +213 796334507; email: moh1059@yahoo.fr (M.E. Ali Ouar), Tel. +213 669868341; email: seifmeddour05@gmail.com (S.E. Meddour), Tel. +213 662240520; email: omarmokrani30@gmail.com (O.B. El Khettab Mokrani)

Received 21 December 2020; Accepted 22 April 2021

ABSTRACT

In Southern Algeria, the only source of drinking water is underground water; however, it is of high salinity. In this area, the solar irradiance is high throughout the year and the quantity of groundwater is enormous; hence, the solar distillation of this water seems to be the cheaper way to solve the shortage encountered in fresh water. This experimental work presents a coupling between the solar chimney power plant and conventional solar still. The aim is to increase the output on distillate by providing the still by supplement and boost heat. To do that, two single slope glass-sides solar stills and solar chimney prototypes have been installed and tested at Ouargla University. One of the two solar stills is coupled with the solar chimney through a copper tube with serpentine shape containing hot brackish water coming from the chimney and crossing its absorber, while the other still remains as witness. Experimental results reveal that the average rise of brackish water temperature in the still's absorber roughly reaches approximately 20°C and the daily output of distillate reaches 6.951 kg/m²/d with an improvement of almost 158% compared with the baseline case.

Keywords: Desalination; Solar distiller; Solar chimney; Integrated; Brackish water; Ouargla

1. Introduction

Access to potable water remains an important challenge in many parts of the world. The oceans contain approximately 96.5% of all water present on Earth. However, this water exists in the form of salt water. The fresh drinking water constitutes only 2.6% of the totality of water on ground being primarily in the rivers, underground or covering the north and the south poles in the ice form. Only 1% of drinkable water can easily be reached by humans and is available for their daily use [1]. Today, approximately 40% of the world population lives under the threat of water deficiency, and this situation will become worse in the near future if trends in daily consumption continue to rise [2].

The provision of potable water to the population stays one of the most important issues for the countries worldwide. The last world reports on fresh water classify Algeria among the top countries most concerned by fresh drinkable water shortage [2]. In the south of Algeria, the groundwater reserves are very important; almost 76% of Algerian ground water are located in this region. The population of these areas uses this water for their daily consumption although its salts concentration reaches sometimes 8 g/L in some locations; whereas the World Health Organization announces that the safe drinking water should contain only 0.5 g/L of dissolved salts [2–5].

The desalination of these brackish waters by the use of fossil energies' methods remains expensive and requires large collective installations; in contrast, the use of solar energy seems more advantageous because it is the suitable renewable source to produce drinkable water considering the important irradiation that characterizes these areas during the year on the one hand and the simplicity of the used devices on the other hand [3].

* Corresponding author.

Conventional solar stills are classified into two categories: active [6] and passive solar stills [7]. Solar distillation using conventional solar stills is the most friendly environmental manner and economical way to distillate the brackish and/or saline water [4]; however, it remains far from satisfying the increasing demand of drinking water considering the poor effectiveness of these apparatuses which a well designed and constructed conventional solar still does not exceed 4.5 L/m^2/d, that is, 1 m^3/m^2/y of distilled water under good operational conditions [8,9]. The essential cause of these low outputs is due mainly to certain points namely: the heat losses towards ambient air through the assembly parts, the heat carried away by the warm distillate, the internal overheating caused by the greenhouse effect, the increase of the condenser temperature due to the latent heat of condensation released by vapors… etc. However, properly and correctly constructed and well maintained, conventional solar stills have been reported to operate successfully for about 20 y or more [2–5].

To improve the daily production of these distillers, several attempts were carried out by researchers. Certain investigators founded useful relationships and correlations governing the heat and mass transfer within these devices; those relations and correlations have been considered as references and bases for the well construction and the high performance of these apparatuses [10–14].

These researchers simulated mathematic models and different designs for different still types in different operational cases and climatic conditions [15,16]. Some of these theoretical studies are followed by experiments in order to validate them and generally, these studies revealed that theoretical and experimental results were in agreement [17].

Pure experimental studies are carried out by other scientists trying to improve the output of these devices by several new techniques [18]. One of these techniques is the heat storage medium within absorber plate; this was achieved by adding materials like gravel [19], stone, alluvial sand [4,3], cement [3], sponge [5], jute cloth [20], rubber, wax, nanocomposite energy storage [21], etc. Those materials increase significantly the distillation period (overnight distillation) by playing the role of heat storage medium which leads to high still outputs.

Adding absorbent materials like dyes, ink, bitumen, charcoal, etc. [22–25] is another technique to enhance the absorption of solar radiance by water which leads to a remarkable enhancement of distillers' yield.

Another researchers' technique is by playing on the characteristics and/or physical parameters of the condenser in order to increase the performance of the condensation phenomenon by diminishing its temperature and/or increasing its surface [26].

Some experimental investigations were carried out by adding semiconductors (metal oxides) to the surface of absorber like K_2O, MgO, MnO_2, TiO_2, Na_2O, ZnO, SiO_2, etc. These latter play the role of photocatalysts leading to high distiller yields and high distillate quality because some of these metal oxides can also play the role of adsorbent materials by adsorbing and/or degrading some organic compounds generally accompanying water like phenols [3–5,27,28].

Using of phase change materials (PCMS) method is another researchers' proposal in aim to profit from the latent heat of phase change for distillation process; the latter feeds absorber plate by supplement energy and consequently leads to high distillation performance [29].

One of the recent method is the use of nano-technology by adding nano-sized particles within the absorber basin to increase the heat and mass-transfer effectiveness and hence to improve the still efficiency [30,21]. The nano-particles added are generally fine particles of metallic or non-metallic compounds.

Some other researchers coupled solar stills with other thermal devices like solar heaters, PV [31,32] and solar chimneys [33]. In the first case, the second device serves to heat water before entering the distiller but in the second case, the water within the absorber is heated twice by direct solar rays and by blackened serpentine of copper-containing heated water coming from the chimney. Other investigators used various techniques by adding evaporation chambers [34] or solar concentrators [35].

To save time and energy, certain researchers used geothermal water to feed directly the distillers [36–41]; although this method gives good outputs, but qualitatively, the distillate will need biological analyzes before consumption because it can contain some volatile organic compounds which are harmful to human health.

In order to enhance the water evaporation rate, other researchers used and carried out a new technique by generating air bubbles through the water within the absorber plate [42–44]. While crossing water, the dry bubbles become humid and after leaving water the vapor transported by these bubbles condenses on a cold surface; this action increases remarkably the quantity of distilled water and reduces the start-up distillation time.

To achieve better performances, several types of solar stills have been proposed by researchers and investigators, namely, multiple-wick solar still [45] and [46], cascaded type [47], multiple-effect solar still [48] and [49], vertical type [50] and [51], conical solar still type [52], inverted absorber type [53] double condensing chamber solar still [54] tubular type [55], "V" type [43], triangular pyramid [56], etc.

In this experimental investigation, an attempt is made to benefit from the thermal energy of the solar chimney and use it to strengthen the distiller energy intake. This method consists of coupling the solar distiller with the solar chimney via a metallic serpentine pipe containing brackish water circulating around the collector of the chimney. After being heated, a part of the hot water is deflected towards the still to further increase the temperature of the brackish water in its absorber plate and consequently leads to rapid evaporation of water and hence to a higher evaporation rate, i.e. a high distillate flow rate; while the other part of heated water serves for domestic uses.

One of the technique for converting solar thermal energy to electrical power is the solar chimney power plant (SCPP); this device can be used in sunny areas especially in arid and semi-arid lands such as southern Algeria where the solar radiation rate is high [2,57]. This plant can also serve to dry food [58], heat air and water and helps to produce hydrogen [59].

The solar chimney power system consists of a vertical cylinder surrounded by a transparent collector. Solar radiations heat the air trapped between the collector and the ground, the latter draws upwards by hydrostatic pressure's difference between the base and the top of the chimney; the air speed launches a turbine-driven generator located at the base of chimney.

Solar desalination and solar chimney plants prototypes were installed and set up at Ouargla University with the aim to achieve our experimental study which consists to couple the two devices (distiller test and solar chimney) in order to reduce the distillation start-up time and to improve the solar still efficiency after strengthening the still's energy intake.

The mean solar irradiance period in the town of Ouargla (latitude 31.95° N, longitude 5.40° E and altitude 141 m) is around 3500 h/y, delivering some 2650 kWh/m^2/y of solar irradiance on the horizontal surface [60]; thus, Ouargla city is a perfect place to install solar plants.

2. Material and method

In order to perform a detailed investigation of the still's yield improvement, small-scale prototypes of two single slope solar stills and one SCPP have been installed and set up at Ouargla University (southern Algeria).

Fig. 1 shows a cross-section of the single-basin type solar still used in our experimental study. The solar still was made of wood 0.04 m thick. Its basin (absorber plate) (0.40 m × 0.60 m × 0.040 m) is made of a galvanized metal tray (to prevent corrosion) 0.003 m thick. The latter was blackened by matte paint to ensure the maximum absorption of solar irradiance. The base of each assembly was further lagged with a 0.04 m thick of polystyrene insulation with a thermal conductivity equal to 0.033 Wm^{-1} K^{-1} to avoid energy loss. The 0.003 m thick removable glass cover of the still was placed such that it makes an angle of 30° with the horizontal which is recommended for Ouargla region [3,4]. To avoid any vapors leakage, the glass cover was sealed firmly by silicone.

Two identical units of solar still were used in our experiments; one serves as the test unit with copper serpentine heater and the other serves as the witness (without serpentine).

Local underground brackish water (≥3 g/L of salts) was supplied to each unit from the tank by means of an adjustable float to maintain the brackish water level (L) in the absorber: 0.005 m ≤ L ≤ 0.010 m to ensure rapid water evaporation [3–5]. The distillate runs along the lower edge of the glass to collect and carry it out of the enclosure into graduated cylinders through plastic tubing.

For the test unit, the copper serpentine tube is bonded inside the absorber to ensure a good heat transfer; while the witness unit remains without serpentine pipe.

Fig. 2 shows the photo of solar chimney which consists of a (126 m^2) collector area. A (PVC) pipe of 0.20 m diameter and 8 m height further isolated by glass wool was used to construct the solar chimney tower which is supported by steel beams. The collector is constructed using steel beams to support a transparent plastic cover and the tower. The collector surface was inclined by about 5° of tilt angle to allow water drainage in the event of rain. The collector height from the ground is 0.4 m near its edge and 0.85 m at the center. For increasing the greenhouse effect, the ground was tainted with black matte paint and covered by black plastic to absorb the maximum solar irradiance.

Fig. 3 shows the photo of the copper serpentine pipe located between the collector of the solar chimney and the blackened ground.

Fig. 4 shows the photo of the experimental devices (solar chimney and solar stills).

During experiments, the measurements of solar irradiance, ambient temperature, wind velocity, temperatures of inner surface of the glass cover and that of brackish water in the basin, water temperature in and out chimney

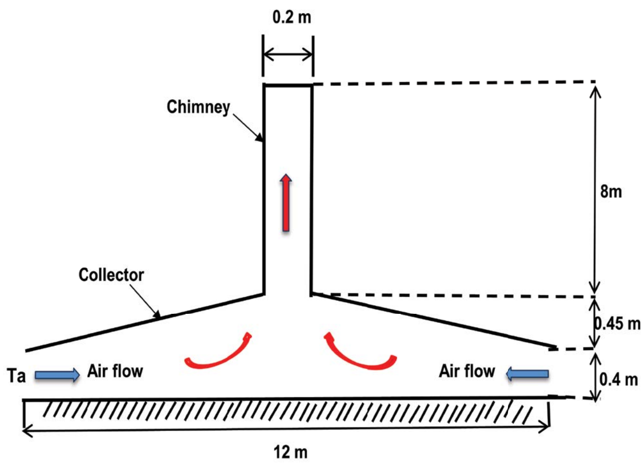

Fig. 2. A cross-section of solar chimney power plant.

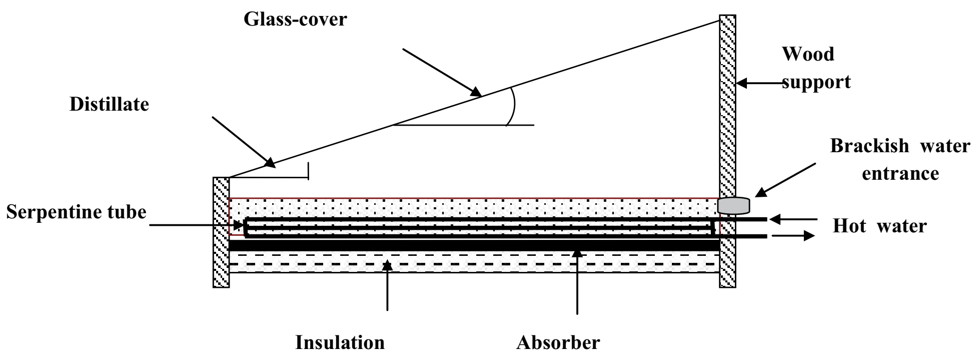

Fig. 1. A cross-section of the test desalination unit.

and distillate amount were made regularly every hour from 07:00 AM until 06:00 PM.

To make the results credible, the measuring process was repeated 3 times during 3 subsequent days. The average values were taken for each unit and then presented as final graphical results. It should be pointed out that before plotting graphics, the hourly yields and the hourly cumulus values are converted into (mL/h/m^2) by dividing them by the absorber's surface (0.24 m^2).

3. Measurement tools

Several tools were used in our experiments to measure some physical and meteorological parameters (Table 1).

- Solar-meter (Mac-Solar) for measuring the solar irradiance (W/m^2) with an accuracy of +1 W/m^2, range of 0–1,500 W/m^2, and an uncertainty <3% ± 1.

Fig. 3. The photo of the serpentine copper tube.

Fig. 4. The photo of the coupled devices solar tower-solar still and the witness.

- Hotwire anemometer (testos416) (40 m/s max) to measure the wind velocity (m/s) and uncertainty of 1.5%.
- Thermocouples (K type) to measure different chimney and still parts' temperatures (°C) with an accuracy of +0.1°C, range of 0–100°C, and uncertainty 1%.
- The previous equipments were integrated with (N-I) acquisition box; with the same module, we can add thermocouples to mixed-signal test systems for offering high-performance data acquisition on PC with National Instrument Signal Express Software (NI-SES).
- Graduates tubes for measuring the distilled water volume (1,000 mL).
- Thermometer to measure the ambient temperature (°C).

4. Results and discussions

Some meteorological parameters such as ambient temperature (T_a), solar irradiance (G) and wind velocity (v) are presented respectively in Figs. 5–7 for Ouargla city,

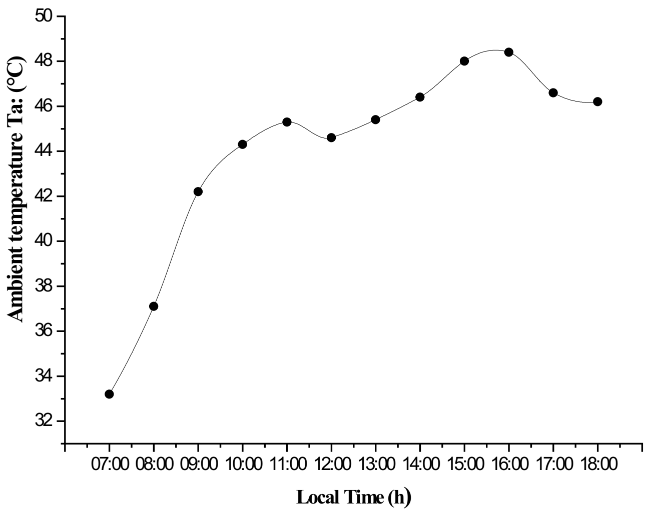

Fig. 5. Ambient temperature vs. local time.

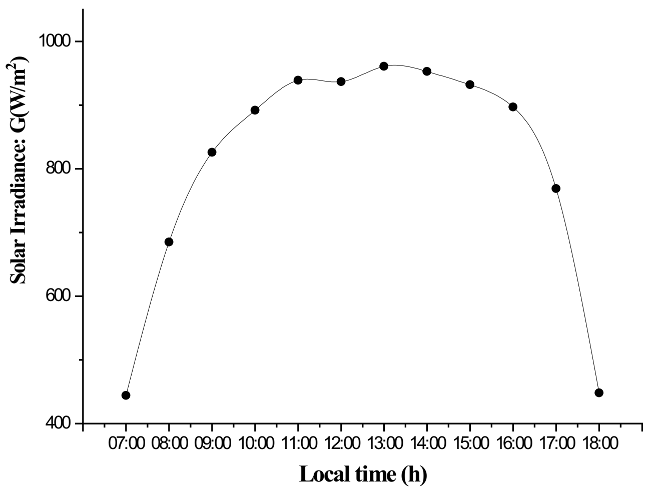

Fig. 6. Solar irradiance vs. local time.

the location of our experiment corresponding to July 24th, 2019 as a chosen day.

The ambient temperature starts with its minimal value of 32.5°C recorded at 07:00 AM to reach its maximum value of 49°C between 16:00 and 17:00 local time. From Fig. 5, we can deduce that Ouargla city has a warm climate.

Fig. 6 displays the variation of solar irradiance (G) vs. local time for the same day. As shown in this figure, eight out of twelve values of solar irradiance are above 800 W/m². The minimum value of 444 W/m² is recorded at 07:00 AM and the upper of 448 W/m² at the end of experiments. The maximum value of 961 W/m² was recorded at 01:00 PM. The mean value for the day is 807 W/m²; so, from those values, we can confirm that this region is a perfect place to build a solar plant.

Fig. 7 shows the variation of the wind velocity versus local time. In this figure, the trend is not regular; the day started without wind ($v = 0$), but at 11:00 AM the wind speed reached 2.5 m/s as the maximum value of the day; however, the wind was not steady either in speed or in direction. It is possible that the wind speed influences the performance of the turbine within the solar chimney when generating electrical power, but with these values ($v < 12$ m/s) it does not have a great effect on the distillation efficiency.

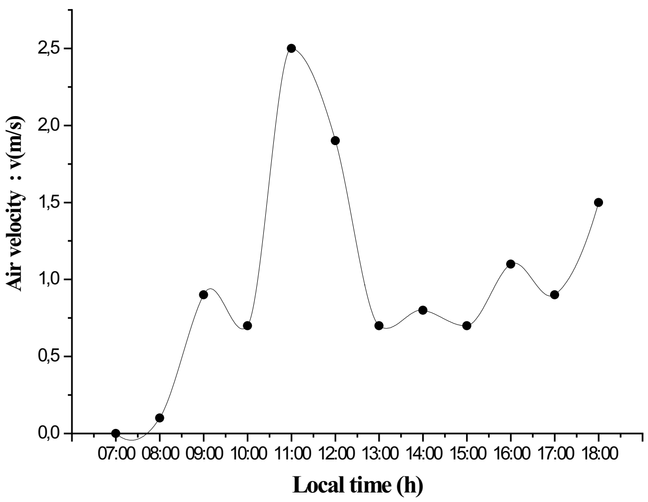

Fig. 7. Wind speed vs. local time.

Fig. 8 displays the variation of absorber temperature (T_{abs}) vs. local time for the test and the witness unit. It's clear that the test unit's curve is always above that of the witness. Concerning the test unit, the absorber temperature (T_{abs}) increases rapidly to reach 80°C at 02:00 PM; in contrast, in the witness unit case, the increase is not accentuated and then the maximum value is recorded at 02:00 PM is only 69°C.

Generally, absorber temperature (T_{abs}) is directly proportional to the brackish water evaporation rate; or otherwise, to the amount of distilled water. The gap between absorber temperatures of the test unit and the witness reaches 11°C; this difference is due of course to the heat carried by water throughout the copper serpentine from the solar chimney to the test unit. This additional heat accelerates the distillation process and leads to high test still's outputs.

As shown in Fig. 9, for the test unit, the two temperatures of water in the basin and that of the absorber plate are almost the same, but always: absorber temperature is slightly higher than that of brackish water within; in our case, the maximum gap between them did not exceed 1°C; so, we can deduce that the convective and conductive heat transfer between brackish water and absorber bonded with serpentine is good and we can write: (absorber temperature ≈ brackish water temperature), or otherwise: absorber temperature = brackish water's temperature +1°C (in our case only).

The condenser temperature (T_g) is one of the important parameter of the solar still performance; low condenser temperature leads generally to high condensation rates of vapours i.e. high still's output. However, in the solar still case, the glass-cover temperature (T_g) remains relatively high because of several phenomena, namely the latent heat released after vapour condensation, the internal greenhouse effect and the heat absorbed by the glass from solar rays.

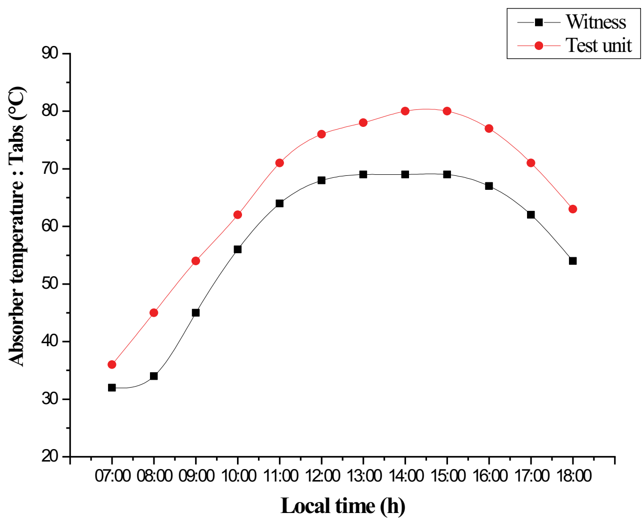

Fig. 8. Absorber temperature for each unit vs. local time.

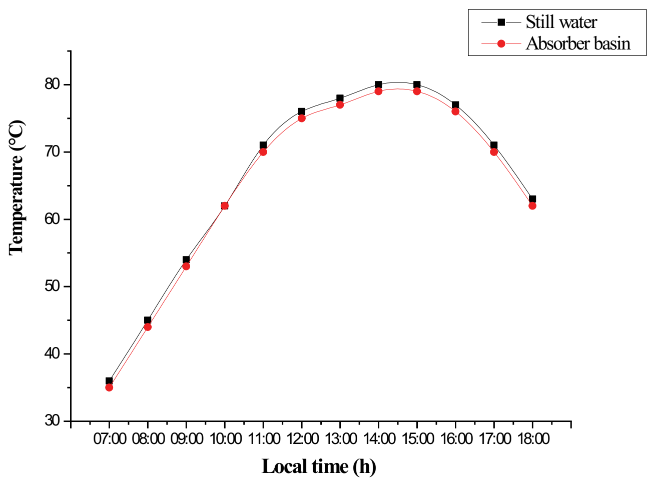

Fig. 9. Absorber water and absorber basin temperatures for the test unit vs. local time.

Fig. 10 shows the curves of glass-cover temperatures (T_g) for two units: the test unit and the witness. The remark that can be pointed out is that the temperature of the test unit's condenser is greater than that of the witness despite the fact that the test unit condenses more than the witness. Since the test unit produces more than the witness and since both condensers are exposed simultaneously to the same solar rays and to the same greenhouse effect, the cause is the high value of the latent heat of condensation released on the test unit's condenser after the large amount of condensed vapour. The next figure representing the difference between the temperature of the absorber and that of the condenser (T_{abs}–T_g) for both units will clarify this point.

Fig. 11 displays the difference between absorber and condenser temperatures (T_{abs}–T_g) for the two units. This difference is generally the still's output key; as much as this difference is large, the amount of distilled water is important. It is clear from curves that the test unit produces more than the witness. The average value of this gap

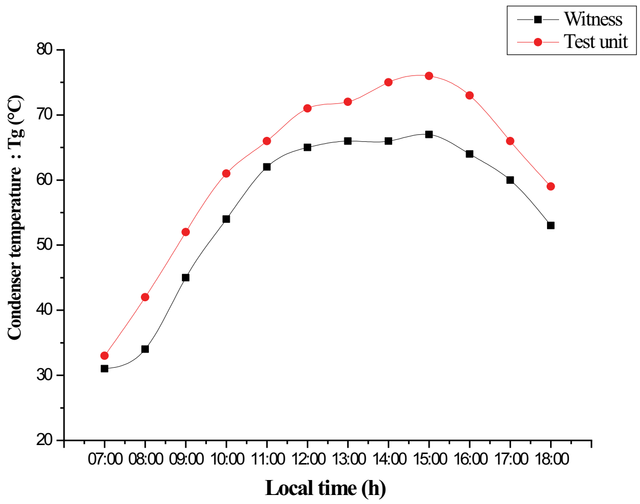

Fig. 10. Condenser temperature for each unit vs. local time.

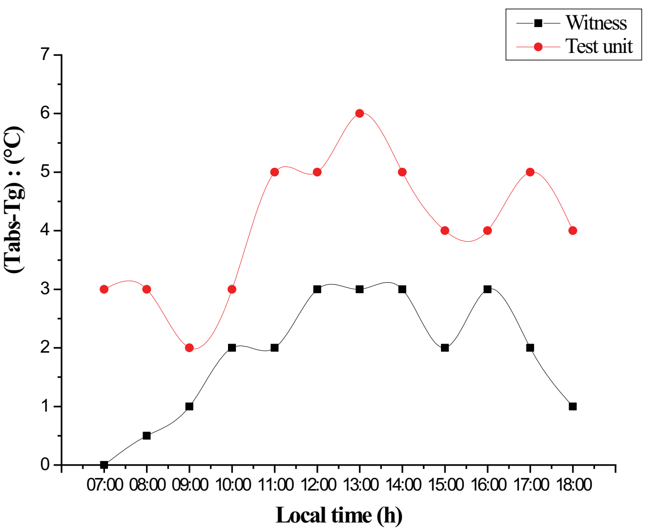

Fig. 11. Temperature difference between absorber and condenser for each unit vs. local time.

(T_{abs}–T_g) is 4.1°C and 1.9°C for the test unit and the witness, respectively.

At the beginning of experiments (07:00 AM), the gap (T_{abs}–T_g) was 3°C for the test unit and 0°C for the witness; which means that the test unit already began to distil while this was not the case for the witness; this is mainly due to the additional heat received by the test unit from the chimney (because in July, the sun rises between 05:30 and 06:00 AM). The supplement heat received by the test unit reduces the distillation start time and accelerates the process.

Fig. 12 displays the temperature profile for the water in and out the solar chimney. The heating becomes intense depending on the solar irradiance. To see clearly the gain in heating temperature, we will take the average of each temperature and compare it. The brackish water enters the solar chimney at the mean temperature of 48°C and leaves it at the mean temperature of 68°C with a mean gain of 20°C; sometimes the gain reaches 30°C at mid-day when solar irradiance is high. So, from this, we can deduce that the solar chimney is a perfect device for absorbing solar radiation and converting it to heat. Finally, as shown in Fig. 9, almost all the heat released by copper serpentine is transferred to brackish water which leads to an average increase of its temperature by about 20°C.

Fig. 13 shows the comparison between the hourly production of the test unit and the witness versus local time. From 07: to 11:00 AM, the gap between the two curves is not large, but from 11:00 PM to the end of experiment,

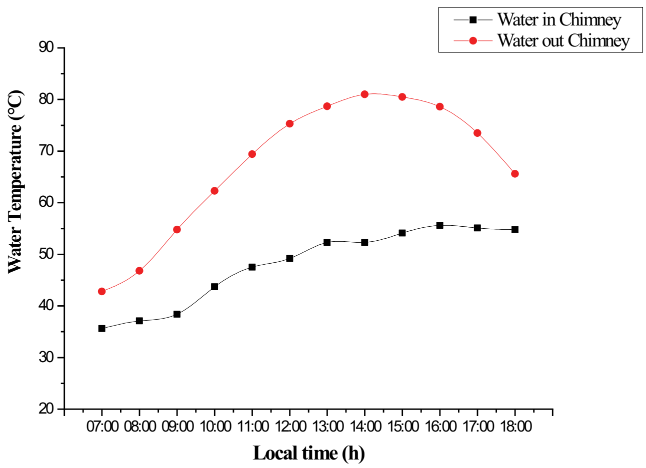

Fig. 12. The temperature of water inlet and outlet chimney vs. local time.

Table 1
Accuracy, measurement range and error limit for various measurement instruments

Instrument	Accuracy	Range	% error (%)
Anemometer	+0.1 m/s	0–40 m/s	1.5
Thermometer	+0.01°C	0–300°C	1
Thermocouple	+0.1°C	0–100°C	1
Solar meter	+1 W/m²	0–1,500 W/m²	<3 ± 1
Graduate tube	+10 mL	0–1,000 mL	1

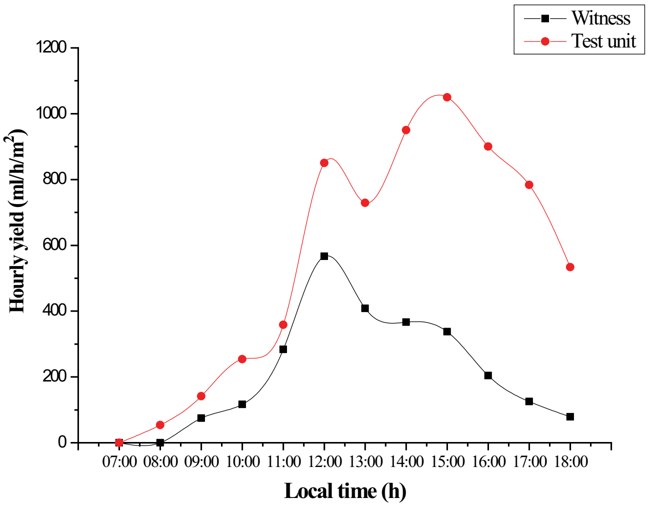

Fig. 13. The hourly yield of distillate for each unit vs. local time.

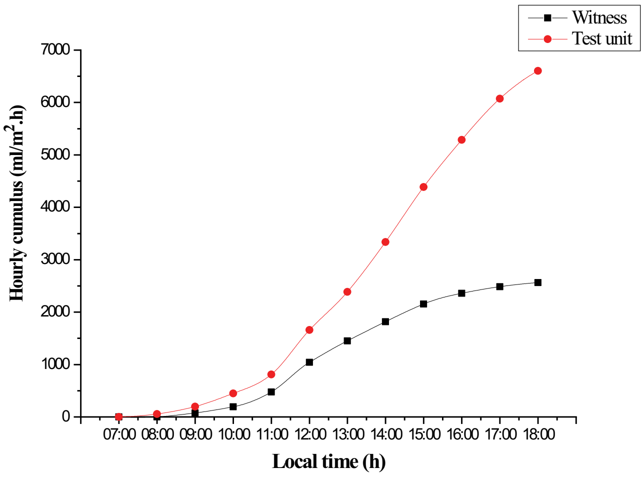

Fig. 14. The hourly cumulus of distillate for each unit vs. local time.

the gap becomes very important exceeding sometimes 600 mL/h/m² of distilled water especially in the afternoon when the solar irradiance begin to decrease. This was explained by the heat stored within the solar chimney's collector under the effect of thermal inertia which continues supplying the test unit with additional heat. The mean value calculated for the hourly yield of the test unit is 550 mL/h/m² compared with only 213 mL/h/m² produced every hour by the conventional unit.

The hourly cumulus for each unit is presented vs. local time in Fig. 14. At the end of experiment, the hourly cumulus becomes the daily (sunny time) output of the solar still. From this figure, it is clear that the test unit produces better than the conventional unit. At 06:00 PM, the daily output is 6,951 and 2,696 mL/m² for the test unit and the witness, respectively; otherwise, the test unit produces more than twice as much as the witness. Thus, the yield improvement was calculated about 158%.

5. Comparison between our study and previous works

Table 2 demonstrates small comparison between our present study and other researcher's works that have been used for the solar chimney for solar desalination worldwide. Also, this table illustrates that the present results have good agreement with that of other researchers.

6. Conclusion

To supply the population by fresh water is still one of the main issue of the countries worldwide. Algeria is classified by recent world water reports among the top countries most concerned by fresh drinkable water scarcity. The population of southern Algeria is still use saline groundwater for their daily consumption although that its salts concentration reaches sometimes 8 g/L in some areas. The use of solar energy to produce fresh water by brackish water desalination is more advantageous because of the great reserves on groundwater and the high solar irradiance that characterize this region.

The existence of a solar chimney for scientific research at the University of Ouargla within the framework of the use of solar thermal energy in the heating of fluids and the production of electricity made us think of the use to increase the efficiency of solar stills by supplying them with hot water, which reduces the start-up time of the distillation

Table 2
Comparison of the present work with some results worldwide

Authors	Study type	Observations
Zuo et al. [61]	Mathematical model	The power production and fresh water productivity increase over 7 h of activity.
Zuo et al. [33]	Experimental study	Integrated system increased the use of solar energy. Maximum freshwater output is about 180 g/h.
Hammadi [62]	Mathematical model	The hybrid system to product power and freshwater driven by solar energy was used. The size of the system has a minor impact on the amount of freshwater generated per unit area. The yield of freshwater power and efficiency are higher in the summer than in the winter.
Ming et al. [63]	3D numerical analysis (ANSYS Fluent)	The amount of water produced increased as the number of spray droplets increased.
Current study	Experimental study	The system consists of a chimney, collector, metallic serpentine pipe and basin solar still gives an improvement of 158% compared to the baseline case.

and contributes to supplying energy to the stills in a very short time.

The coupling between the chimney and the stills allowed a benefit of around 20°C compared to the usual case, and this benefit helps to double production by 158% because the active still was able to produce around 7 kg/m²/d of distillate in (July 2019).

Based on this experience, we will work on a new idea, which is to place the chimney directly above the water basin and to condense steam in pipes in the basement, where we expect this idea will be a quantum leap in the field of solar distillation.

Symbols

G	—	Solar irradiance, W/m^2
T_a	—	Ambient temperature, °C
T_{abs}	—	Absorber temperature, °C
T_g	—	Glass-cover temperature, °C

References

[1] S.A. Kalogirou, Seawater desalination using renewable energy sources, Prog. Energy Combust. Sci., 31 (2005) 242–281.
[2] M.H. Sellami, H. Bouguettaia, D. Bechki, M. Zeroual, S. Kachi, S. Boughali, B. Bouchekima, H. Mahcene, Effect of absorber coating on the performance of a solar still in the region of Ouargla (Algeria), Desal. Water Treat., 51 (2013) 6490–6497.
[3] M.H. Sellami, R. Touahir, S. Guemari, K. Loudiyi, Use of Portland cement as heat storage medium in solar desalination, Desalination, 398 (2016) 180–188.
[4] M.H. Sellami, S. Guemari, R. Touahir, K. Loudiyi, Solar distillation using a blackened mixture of Portland cement and alluvial sand as a heat storage medium, Desalination, 394 (2016) 155–161.
[5] M.H. Sellami, T. Belkis, M.L. Aliouar, S.D. Meddour, H. Bouguettaia, K. Loudiyi, Improvement of solar still performance by covering absorber with blackened layers of sponge, Groundwater Sustainable Dev., 5 (2017) 111–117.
[6] A.A. El-Sebaii, S. Aboul-Enein, M.R.I. Ramadan, A.M. Khallaf, Thermal performance of an active single basin solar still (ASBS) coupled to shallow solar pond (SSP), Desalination, 280 (2011) 183–190.
[7] M. Sharma, A.K. Tiwari, D.R. Mishra, A review on desalination of water using single slope passive solar still, Int. J. Dev. Res., 6 (2016) 10002–10012.
[8] F.R. Annon, Seawater and Brackish Water Desalination in the Middle East, North Africa and Central Asia Final Report Annex 1 Algeria, 2004, pp. 1–36.
[9] M.G. Green, D. Schwarz, Extracting Drinking Water from Salt Water: An Overview of Desalination Options for Developing Countries, Gtz-Gate, 2001, pp. 1–6. Available at: http://www.gtz.de/gate/gateid.afp.
[10] A.F. Elsafty, H.E. Fath, A.M. Amer, Mathematical model development for a new solar desalination system (SDS), Energy Convers. Manage., 49 (2008) 3331–3337.
[11] M.I.M. Shatat, K. Mahkamov, Determination of rational design parameters of a multi-stage solar water desalination still using transient mathematical modelling, Renewable Energy, 35 (2010) 52–61.
[12] R.V. Dunkle, Solar Water Distillation: The Roof Type Still and a Multiple Effect Diffusion Still, Proc. International Heat Transfer Conference, University of Colorado, USA, 1961, pp. 895–902.
[13] Z. Chen, X. Ge, X. Sun, L. Bar, Y.X. Miao, Natural convection heat transfer across air layers at various angles of inclination, Eng. Thermophys., 26 (1984) 211–220.
[14] R.S. Adhikari, A. Kumar, A. Kumar, Estimation of mass-transfer rates in solar stills, Int. J. Energy Res., 14 (1990) 737–744.
[15] A. Ahsan, M. Imteaz, A. Rahman, B. Yusuf, T. Fukuhara, Design, fabrication and performance analysis of an improved solar still, Desalination, 292 (2012) 105–112.
[16] H.N. Panchal, S. Patel, An extensive review on different design and climatic parameters to increase distillate output of solar still, Renewable Sustainable Energy Rev., 69 (2017) 750–758.
[17] C. Ali, K. Rabhi, R. Nciri, F. Nasri, S. Attyaoui, Theoretical and experimental analysis of pin fins absorber solar still, Desal. Water Treat., 56 (2015) 1705–1711.
[18] H. Sharon, K.S. Reddy, D. Krithika, L. Philip, Experimental performance investigation of tilted solar still with basin and wick for distillate quality and enviro-economic aspects, Desalination, 410 (2017) 30–54.
[19] S. Deshpande, J. Deepak, N. Patel, Enhancement of Solar Still with Internal, External Reflector and Black Granite Gravel, International Conference on Futuristic Trends in Engineering, Science, Pharmacy and Management, Vadodara, India, 2016, pp. 31–34.
[20] M. Sakthivel, S. Shanmugasundaram, T. Alwarsamy, An experimental study on a regenerative solar still with energy storage medium—Jute cloth, Desalination, 264 (2010) 24–31.
[21] A. Elfasakhany, Performance assessment and productivity of a simple-type solar still integrated with nanocomposite energy storage system, Appl. Energy, 183 (2016) 399–407.
[22] S. Abdallah, M.M. Abu-Khader, O. Badran, Effect of various absorbing materials on the thermal performance of solar stills, Desalination, 242 (2009) 128–137.
[23] P.K. Srivastava, S.K. Agrawal, A. Agrawal, Effect of absorber material on the performance of basin type solar still with multiple floating porous absorbers, Int. J. ChemTech Res., 5 (2013) 1046–1053.
[24] A.K. Rajvanshi, Effect of various dyes on solar distillation, Sol. Energy, 27 (1981) 51–65.
[25] M.M. Naim, M.A.A. El Kawi, Non-conventional solar stills Part 1. Non-conventional solar stills with charcoal particles as absorber medium, Desalination, 153 (2003) 55–64.
[26] Z.M. Omara, A.S. Abdullah, A.E. Kabeel, F.A. Essa, The cooling techniques of the solar stills' glass covers – a review, Renewable Sustainable Energy Rev., 78 (2017) 176–193.
[27] S.G. Patel, S. Bhatnagar, J. Vardia, S.C. Ameta, Use of photocatalysts in solar desalination, Desalination, 189 (2006) 287–291.
[28] U.I. Gaya, A.H. Abdullah, Heterogeneous photocatalytic degradation of organic contaminants over titanium dioxide: a review of fundamentals, progress and problems, J. Photochem. Photobiol., C, 9 (2008) 1–12.
[29] T. Arunkumar, R. Velraj, G.O. Prado, D.C. Denkenberger, O. Mahian, R. Sathyamurthy, K. Vinothkumar, A. Ahsan, Effects of concentrator type and encapsulated phase change material on the performance of different solar stills: an experimental approach, Desal. Water Treat., 87 (2017) 1–13.
[30] B. Gupta, A. Kumar, P. V Baredar, Experimental investigation on modified solar still using nanoparticles and water sprinkler attachment, Front. Mater. 4 (2017) 23, doi: 10.3389/fmats.2017.00023.
[31] K.S. Reddy, H. Sharon, Performance Investigation of Combined Solar Desalination and Hot Water System, SWC-ISES, Conference Proceedings, 2015, pp. 8–12.
[32] A.M. Manokar, D.P. Winston, A.E. Kabeel, S.A. El-Agouz, R. Sathyamurthy, T. Arunkumar, B. Madhu, A. Ahsan, Integrated PV/T solar still-a mini-review, Desalination, 435 (2018) 259–267.
[33] L. Zuo, Y. Yuan, Z. Li, Y. Zheng, Experimental research on solar chimneys integrated with seawater desalination under practical weather condition, Desalination, 298 (2012) 22–33.
[34] Z.S. Akhatov, A.S. Khalimov, K.K. Saidov, A study of the influence of inlet air flow humidity and temperature on thermal efficiency of an evaporation chamber of a solar desalination plant, Appl. Sol. Energy, 52 (2016) 109–114.
[35] T. Arunkumar, A.E. Kabeel, Effect of phase change material on concentric circular tubular solar still-Integration meets enhancement, Desalination, 414 (2017) 46–50.
[36] C. Karytsas, Low Enthalpy Geothermal Energy Driven Seawater Desalination Plant on Milos Island—A Case Study, Proc.

Mediterr. Conf. Renew. Energy Sources Water Prod., Santorini, Greece, 1996, pp. 128–131.

[37] A. Ophir, Desalination plant using low grade geothermal heat, Desalination, 40 (1982) 125–132.

[38] M. Rodriguez-Gironés, J. Perez, J. Veza, A Systematic Approach to Desalination Powered by Solar, Wind and Geothermal Energy Sources, Mediterranean Conference on Renewable Energy Sources for Water Desalination, Santorini,. 1996, pp. 20–25.

[39] K. Bourouni, R. Martin, L. Tadrist, Analysis of heat transfer and evaporation in geothermal desalination units, Desalination, 122 (1999) 301–313.

[40] K. Bourouni, J.C. Deronzier, L. Tadrist, Experimentation and modelling of an innovative geothermal desalination unit, Desalination, 125 (1999) 147–153.

[41] K. Bourouni, M.T. Chaibi, L. Tadrist, Water desalination by humidification and dehumidification of air: state of the art, Desalination, 137 (2001) 167–176.

[42] T. Arunkumar, R. Jayaprakash, A. Ahsan, D. Denkenberger, M.S. Okundamiya, Effect of water and air flow on concentric tubular solar water desalting system, Appl. Energy, 103 (2013) 109–115.

[43] P.U. Suneesh, R. Jayaprakash, T. Arunkumar, D. Denkenberger, Effect of air flow on "V" type solar still with cotton gauze cooling, Desalination, 337 (2014) 1–5.

[44] H. Ben Halima, N. Frikha, S. Gabsi, Experimental study of a bubble basin intended for water desalination system, Desalination, 406 (2017) 10–15.

[45] M.S. Sodha, A. Kumar, G.N. Tiwari, R.C. Tyagi, Simple multiple wick solar still: analysis and performance, Sol. Energy, 26 (1981) 127–131.

[46] G.N. Tiwari, Demonstration plant of a multi wick solar still, Energy Convers. Manage., 24 (1984) 313–316.

[47] S. Satcunanathan, H.-P.Hansen, An investigation of some of the parameters involved in solar distillation, Sol. Energy, 14 (1973) 353–363.

[48] H. Tanaka, T. Nosoko, T. Nagata, A highly productive basin-type-multiple-effect coupled solar still, Desalination, 130 (2000) 279–293.

[49] H. Tanaka, T. Nosoko, T. Nagata, Parametric investigation of a basin-type-multiple-effect coupled solar still, Desalination, 130 (2000) 295–304.

[50] T. Kiatsiriroat, S.C. Bhattacharya, P. Wibulswas, Transient simulation of vertical solar still, Energy Convers. Manage., 27 (1987) 247–252.

[51] J.P. Coffey, Vertical solar distillation, Sol. Energy, 17 (1975) 375–378.

[52] B.W. Tleimat, E.D. Howe, Comparison of plastic and glass condensing covers for solar distillers, Sol. Energy, 12 (1969) 293–304.

[53] S. Suneja, G.N. Tiwari, Optimization of number of effects for higher yield from an inverted absorber solar still using the Runge-Kutta method, Desalination, 120 (1998) 197–209.

[54] G.N. Tiwari, A. Kupfermann, S. Aggarwal, A new design for a double-condensing chamber solar still, Desalination, 114 (1997) 153–164.

[55] S.H. Hammadi, D.M.H. Al-Shamkhee, H.A. Jabar, Experimental study of the performance of tubular solar still in Najaf city, Int. J. Energy Environ., 6 (2015) 587.

[56] P.N. Kumar, A.M. Manokar, B. Madhu, A.E. Kabeel, T. Arunkumar, H. Panchal, R. Sathyamurthy, Experimental investigation on the effect of water mass in triangular pyramid solar still integrated to inclined solar still, Groundwater Sustainable Dev., 5 (2017) 229–234.

[57] A.R. Shahreza, H. Imani, Experimental and numerical investigation on an innovative solar chimney, Energy Convers. Manage., 95 (2015) 446–452.

[58] A.G. Ferreira, C.B. Maia, M.F.B. Cortez, R.M. Valle, Technical feasibility assessment of a solar chimney for food drying, Sol. Energy, 82 (2008) 198–205.

[59] N. Monnerie, H. von Storch, A. Houaijia, M. Roeb, C. Sattler, Hydrogen production by coupling pressurized high temperature electrolyser with solar tower technology, Int. J. Hydrogen Energy, 42 (2017) 13498–13509.

[60] M.H. Sellami, K. Loudiyi, Electrolytes behavior during hydrogen production by solar energy, Renewable Sustainable Energy Rev., 70 (2017) 1331–1335.

[61] L. Zuo, Y. Zheng, Z. Li, Y. Sha, Solar chimneys integrated with sea water desalination, Desalination, 276 (2011) 207–213.

[62] S.H. Hammadi, Combined solar chimney power plant and solar still, Basrah J. Eng. Sci., 16 (2016) 100–107.

[63] T. Ming, T. Gong, R.K. de Richter, C. Cai, S.A. Sherif, Numerical analysis of seawater desalination based on a solar chimney power plant, Appl. Energy, 208 (2017) 1258–1273.