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Experimental parametric study of solar still coupled with humidification–dehumidification desalination system

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ABSTRACT

Drinking water consumption rises increasingly in our planet given the dense use in industrial and agricultural sector and increase of the world population. For this reason, desalination presents the best solution to fight against this problem. A review of the vast literature available on solar distillation systems has revealed many observations about the design, performance, and the limitation of freshwater production of solar distillation systems. Solar stills are used for solar distillation plants due to its simplicity in construction and operation, low cost, and however the yield is low. A lot of research work is undertaken to improve the productivity of the conventional still. This paper tackles an experimental parametric study of solar still coupled with humidification–dehumidification desalination system which is located at Sfax engineering national school in Tunisia. The humidification–dehumidification desalination system is made of four elements: the inner condenser, the humidifier, the water solar heater, and the air solar heater. The results clearly indicated that the performance of the solar distiller increases proportionally with the solar irradiation and outlet water temperature of solar collector. The performance of the solar distiller is experimentally studied, to find out the best factors enhancing still productivity. The results show that decreasing of water depth increases the yield product. The experiment is carried out during the summer climatic conditions of Tunisia. The economic analysis of the solar still was studied, and the lifetime for a solar still unit is about 20 years.

Keywords: Solar still; Desalination; Air and water solar heater; Condenser; Humidifier

1. Introduction

Freshwater presents the essential element for human life. Solar still presents a simple method and economical process to produce freshwater by using solar energy. However, the conventional solar distiller is characterized by law productivity. In this context, several designs and a lot of studies have been conducted to ameliorate the productivity of solar distiller. Naim and AbdElKawi [1] tested the solar distiller system with energy storage media at its base by Bassam and Himzeh [2], who presented an experimental study of a solar distiller system with different size sponge cubes placed in the basin of the solar distiller. On their part, Kalidasa Murugavel and Sridhar [3] presented an experimental study of optimized solar still up to a minimum depth of saline water in the basin while adding different wick materials in the basin, like cotton cloth, sponge sheet, and aluminum rectangular fin arranged in different configurations in the basin water. Moreover, Yadav and Yadav [4] studied the solar distiller by incorporating inverted absorber asymmetric line-axis compound parabolic concentrating collector and concluded that freshwater increased more than the conventional solar distiller system because in the later, the solar radiation is received directly by the basin or solar still water

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and is only source of energy for raising the water temperature. The various parameters that affect the yield productivity of solar distiller system coupled with the water solar heater and the effect of inclination of water collector of conventional solar distiller were optimized by Tanaka and Nakatake [5]. On their part, Zaki et al. [6] presented an experimental study of an active solar distiller integrated within a solar water heater and found that the maximum increase in the yield was up to 33%. As for Ahsan and Fukuhara [7], they presented a new model of heat and mass transfer of a tubular still system. They found that the heat balance of the humid air and the mass balance of the water vapor in the humid air were formulized for the first time. Sakthivel et al. [8] presented an experimental study of an optimized solar distiller unit by adding jute cloth in vertical position in the middle of the basin water and another row of jute cloth attached to the distiller wall. A rotating horizontal shaft coupled with a wind turbine and solar water collector still integrated to main device of solar distiller system as a hybrid system of distillation was studied by Eltawil and Zhengming [9].They found that the inclined water still produced higher output yield than that of the main device of solar distiller unit by about 29.17%. Arslan [10] ameliorated the performance of various concepts of active solar distiller systems under closed cycle mode experimentally and concluded that the circular box active solar still concept produced the highest overall daily efficiency. A comprehensive review has been done on different types of solar distillers systems by Kaushal and Varun [11]. El-Zahaby et al. [12] presented a new concept of a solar distiller unit with a flashing chamber to ameliorate the freshwater yield. For example, Zeinab and Ashraf [13] developed a rotating shaft with horizontal axis introduced near the water surface of the basin water of the solar distiller unit to improve the yield productivity. They coupled this solar still with an electrical motor to rotate the shaft. They found that this new concept of the solar still improved by 5.5% in July, 5% in June, and 2.5% at May. On the other hand, Tiwari et al. [14] presented an exergoeconomic and enviroeconomic analysis of an active solar still unit coupled with the photovoltaic flat plate. They found that the thermal efficiency of the solar still under study is low. On their part, Estahbanati et al. [15] presented a parametric study of the effect of number of stages on the yield productivity of multi-effect active solar distiller unit in continuous and non-continuous mode operating. As for Tiwari and Lovedeep Sahota [16], they presented a parametric study of the solar still unit with different types of solar energy. As for Ben Bacha and Zhani, [17] and Zarzoum et al. [18,19], they developed a new design of solar distiller system coupled with a water solar heater and a separate condenser chamber coupled in the present solar still system to increase the productivity. In this work, an experimental study of a new solar still unit is carried out.

To increase the yield production of this optimized solar unit, the following elemets are added:

- A water solar collector to increase the water temperature in the bassin of the optimized solar still.
- Material energy storage in the basin of the solar still system to extend the function of the solar still unit at night.
- An humidifier composed of a pulverizer and a packed bed to increase the exchange surface and the residence time of air and water inside the solar still to increase the heat and mass transfer, and thereafter improve the production of freshwater system to increase the water temperature and the area of water in contact with the air which can accelerate the rate of evaporation.
- A plane air solar collector coupled with the humidifier to improve the flow rate of the evaporated water.
- An inner condensation chamber in the optimized solar still system where condensation is produced at a temperature below that of the glass cover.

This paper presents an experimental study to improve the performance of a solar distiller system at different water depths in the basin according to the climatic conditions of Tunisia. The freshwater output, the water, the basin temperature, ambient temperature, and vapor temperature air were measured. This solar still unit consists of four main parts: an internal condenser chamber, humidifier, solar water, and an air heater.

2. Still system

The solar distiller system consists of four main parts: an internal condenser chamber, humidifier, solar water, and an air heater. The condensed water is collected from the bottom of the condenser chamber of the solar distiller, while the salty water exiting the humidifier at the bottom of the humidifier will be either recycled and combined at the entry point or rejected in case of an increase of saltiness rates.

2.1. Design and construction

Figs. 1 and 2 present the photograph of the experimental setup and the construction of solar distiller unit using solar energy. The detailed specification of all components of the solar still is presented in Table 1. The proposed solar distillation unit consists of four systems; air and water solar heating, condenser chamber, and humidifier coupled with the solar still system. The solar still unit is useful especially in summer when the solar irradiation reaches its high values. For this reason, it is important to improve the experimental behavior of the modified solar distiller in summer. The experimental setup of the optimized solar unit prototype was made, installed, and tested in the climatic conditions of Tunisia. This part of the work concerns the design and the construction of

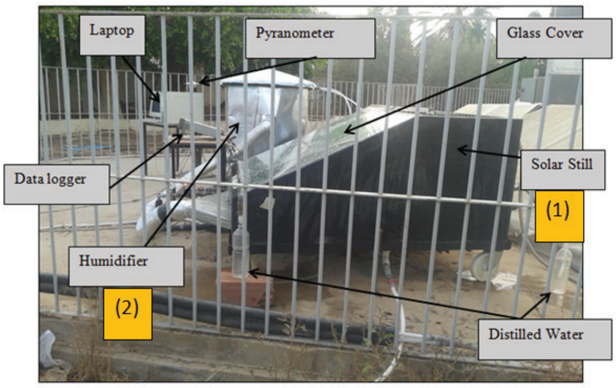

Fig. 1. Photographic view of experimental setup.

the optimized solar still unit. The basin of the solar distiller unit which is painted black is used to improve the yield of the solar energy during the day absorbed.

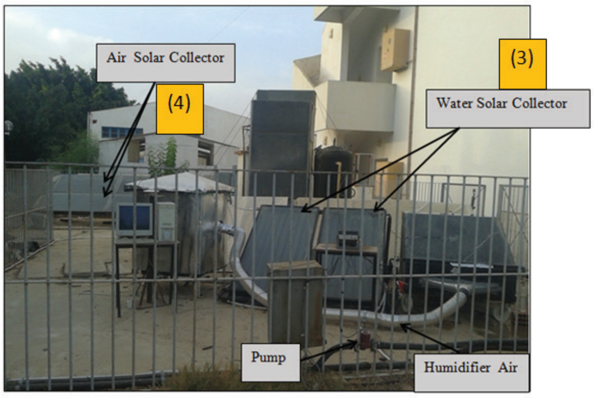

Fig. 2. Photograph of the experimental solar distiller unit (front view).

Table 1
Properties of each component of the solar still unit

Components of solar still	Specifications
Solar still	
Length	1 m
Width	1 m
Thickness of glass cover	0.004 m
Inclination of glass cover	30°
Insulation thickness	50 mm
Water solar collector	
Area of the collector	2 m^2
Tube material	Copper tubes
Plate thickness	0.002 m
Riser-outer diameter	0.0127 m
Riser thickness	0.56 × 10
Thickness of insulation	0.1 m
Weight of the collector	48 kg
Angle of collectors	45°
Loss coefficient	4.8 W/m^2.K
Absorber surface	Paint mat black
Air solar collector	
Area of the collector	2 m^2
Absorptivity of glass cover	0.1
Riser thickness	0.56 × 10 m
Thickness of insulation	Polyurethane, 0.1 m
Weight of the collector	48 kg
Angle of collectors	45°
Absorptivity of plate	0.9
Humidifier	
Size	0.5 m × 0.5 m × 0.7m
Garnishing	Cellulosic material
Inner condenser	
Size	0.5 m × 0.5 m × 0.5m

The glass cover of thickness 4 mm of the optimized solar still system is used as the condensing surface. The freshwater output is collected in a channel fixed to the basin to receive the yield; the solar distiller prototype is connected to the solar water collector to increase the temperature of the water placed in the basin and the water pulverized into the humidifier. The water and air solar heater is 2 m long and 1 m width, and composed of a single glass cover and an absorber to improve the absorbed solar energy. Moreover, this solar distiller unit is coupled with an air solar heater to ameliorate the outlet air temperature in the humidifier by cons increase the exchange surface and the residence time of humidifier in the basin of solar distiller and the humidifier and to improve the heat and mass transfer, and ameliorate the productivity of distillate water.

The amount of evaporative water produced in the humidifier is transported toward the tower of condensation where it comes in contact with the surface temperature which is lower than the dew point of the humid air. The yield productivity of the produced distiller water is collected in the condensation chamber of the optimized solar system and in a channel fixed to the basin to receive the yield.

2.2. Instrumentation

Various parameters have to be experimentally studied in order to improve the performance of the new concept of the solar distiller unit with a condenser chamber coupled with water and an air solar heater and a humidifier. The distilled water productivity, the water, basin, vapor air, and ambient temperature are measured. Experimental instruments with reference, application, sensibility, and accuracy are given in Table 2.

2.3. Temperature measurements

Thermocouples are located and placed at the inlet and outlet of solar distiller and the air and water solar collectors. They save the different temperatures of the glass cover, the basin water, the air and water, and the ambient temperature. The temperature sensors (thermocouples) measure the temperatures and store the values in data logger connected to a laptop where the readings are recorded in a laptop. Temperature sensors have a least count of 0.1°C.

2.4. Radiation measurements

The pyranometer is connected to the data logger to measure solar insolation with ±1 W/m^2 accuracy and 12.29 μV/Wm^2 sensibility placed in a horizontal plane adjacent to the collector. It is connected to the data logger which measures the solar irradiation and stores it during the experiment.

2.5. Data logger

Various thermocouples, which are used to measure the evolution of the temperature of a particular place, are connected to the overtime data recorder (data logger) that is simply fixed with some program software and plugged in with computer. The computer records the data during a sunny day.

Table 2
Experimental instruments with reference, application, sensibility, and accuracy

Sensor/type	Reference	Application	Sensibility	Accuracy
Pyranometer	CIMEL CE 1180	Solar radiation	12.29 µV/Wm^2	±1 W/m^2
Pt 100	PRO-SL 100PV	Temperature	0.3799 Ω/°C	
K-type thermocouple		Temperature		±1.5
TH 100	KIMO TH 100-AOD	Humidity	±0.159mA%	±2%

These thermocouples, which are connected with logger and fixed with different channels, indicate the channel-wise simulation of temperature. These channels measure the different output and input parameters. The view of the channel and the program running on computer are presented in Fig. 1.

3. Energy balance equations for solar still

The general mathematical model of the solar distiller using thermal and mass balance can be written as follows:

- Thermal modeling for the glass cover

$$M_v C_v dT_g = IA_v dt + h_{rwv}(T_w - T_g)dt + h_{\text{evp}}(T_w - T_g)dt - h_{rc}(T_g - T_{\text{amb}})dt \quad (1)$$

- Thermal modeling for the basin absorber

$$M_b C_b dT_b = IA_b dt - h_{cbw}(T_b - T_w)dt - U_{\text{loss}}(T_b - T_{\text{amb}})dt \quad (2)$$

- Thermal modeling for the water basin

$$\left(M_w C_w\right)dT_w = IA_w dt + h_{cbw}(T_b - T_w)dt - h_{rwv}(T_w - T_g)dt - h_{cwv}\left(T_w - T_g\right)dt - h_{\text{evp}}(T_w - T_g)dt \quad (3)$$

- The water condensation rate in the solar still system can be expressed as follows:

$$d_m = \frac{h_{\text{evp}}(T_w - T_g)3600}{L} \quad (4)$$

where,
The evaporation coefficient

$$h_{\text{evp}} = 16.273(10^{-3})h_{cwv}\frac{(P_w - P_v)}{T_w - T_g} \quad (5)$$

The convection coefficient

$$h_{cwv} = 0.084\left[T_w - T_g + \frac{(P_w - P_V)(T_w + 273)}{268.9\times 10^3 - P_w}\right]^{\frac{1}{3}} \quad (6)$$

The coefficient of heat transfer by convection

$$h_{cbw} = 135\,\text{W/m}^2\text{K} \quad (7)$$

The radiation coefficient from the water to the glass cover

$$h_{rwv} = \varepsilon_{\text{eff}}\sigma\left[\frac{(T_w + 273)^4 - (T_g + 273)^4}{T_w - T_g}\right] \quad (8)$$

$$\varepsilon_{\text{eff}} = \left[\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_v} - 1\right]^{-1} \quad (9)$$

The coefficient of convective radiative heat transfer in the solar still system from glass cover to the ambient air

$$h_{cr} = h_{cva} + h_{rva} \quad (10)$$

$$h_{rva} = \varepsilon_v\sigma\left[\frac{(T_g + 273)^4 - (T_{\text{amb}} + 273)^4}{T_g - T_{\text{amb}}}\right] \quad (11)$$

$$h_{cva} = 5.7 + 3.8V_{\text{wind}} \quad (12)$$

- Calculation of efficiency

$$n_{\text{hourly, thermal}} = \frac{m_{ew}\times L}{[A_c \times I_c(t) + A_s \times I_s(t)]\times 3600}\times 100 \quad (13)$$

where $I_c(t)$ is incident solar intensity on collector, W/m^2 and $I_s(t)$ is incident solar intensity on solar still, W/m^2

3.1. Approximation of mathematical models of solar distiller unit

The analytical solution of equations of the mathematical model of solar distiller unit is impossible. Therefore, the obtained global model of the solar unit distillation is converted into a set of algebraic system equations to make them ordinary equations by the functional approximation method of orthogonal collocation (OCM).

The OCM approximates the solution of the obtained model by a polynomial trial function and make them ordinary equations.

3.2. Formulation of the approximation method of solar distiller unit

By substituting the approximation method of the global model of the solar distiller unit presented earlier in the initial system formed by partial derivatives equations to render them ordinary equations according to the time localized in every solar still system reduced dynamic model,

$$\frac{dT_{vi}}{dt}=\frac{1}{M_vC_v}(IA_v+h_{rwv}(T_{wi}-T_{vi})+h_{\text{evp}}(T_{wi}-T_{vi})-h_{rc}(T_{vi}-T_{\text{amb}})) \quad (14)$$

$$\frac{dT_{bi}}{dt}=\frac{1}{M_bC_b}(IA_b-h_{cbw}(T_{bi}-T_{wi})-U_{\text{loss}}(T_{bi}-T_{\text{amb}})) \quad (15)$$

$$\frac{dT_{wi}}{dt}=\frac{1}{(M_wC_w)}(IA_W+h_{cbw}(T_{bi}-T_{wi}) -h_{rwv}(T_{wi}-T_{vi})-h_{cwv}(T_{wi}-T_{vi}) -h_{evp}(T_{wi}-T_{vi})) \quad (16)$$

4. Experimental results of the new solar distillation unit

4.1. Climatic conditions

Figs. 3 and 4 present the measured climatic conditions, the solar irradiation, and the ambient temperature for a typical day of July in the city of Sfax, Tunisia. It was observed that during this sunny day, these climatic conditions increased proportionally and reached a maximum value at around noon period and then decreased.

4.2. Yield productivity of the new solar distillation unit

Variations of the produced distillate water on different days are shown in Fig. 5. It is clear, therefore, that the use of the preheater (water solar collector) and black absorber combined with a solar distiller is very beneficial for the yield of distillate water, because the inlet water temperature in the optimized solar distiller is mainly due to the effect of this preheater system with the aim of increasing the heat exchange surface and the absorption of the radiation. It can be seen that the highest productivity is about 9,1 L/d occurring in August (19/08/2015). We note that the curve of the total yield production is almost zero at the beginning of the day. The productions of solar distiller showed that freshwater increases when the brine temperature rises. This is because of the minimum convective and radiation heat losses dealing with the mass flow rate of circulating brackish water. Besides, the lowest feedwater flow rate gives minimum thickness of water film moving over the stepped surface of the solar distiller (basin of the optimized solar still) and hence gives maximum outlet water temperature and subsequently improves the evaporation and the condensation process.

4.3. Effect of water depth

The influence of water depth on the condensate produced is presented in Fig. 6. The solar flux can reach almost 1,050 W/m² in August (19/08/2015). From the graphs, it is clear that the freshwater output decreases with the increase in the depth of water. Therefore, the main objective of this work is to show the performance of the optimized new solar system. The maximum distillate collected is 9,1 L/d for the water depth of 0.01 m. We note that the freshwater increases with the decrease of different water depths in the water basin of the optimized solar still. As consequence, it is interesting

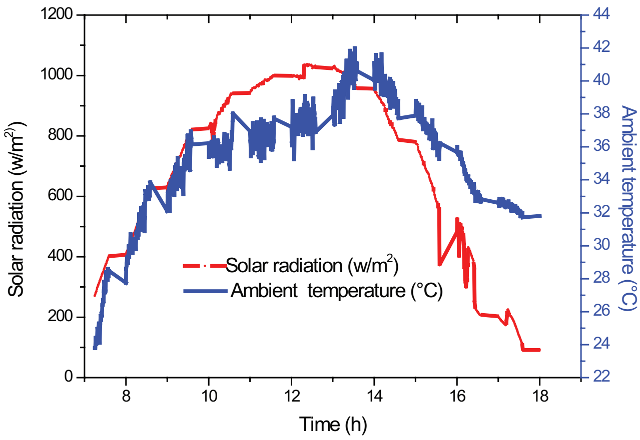

Fig. 4. Ambient temperature and solar irradiation measured during a typical day (19/082015).

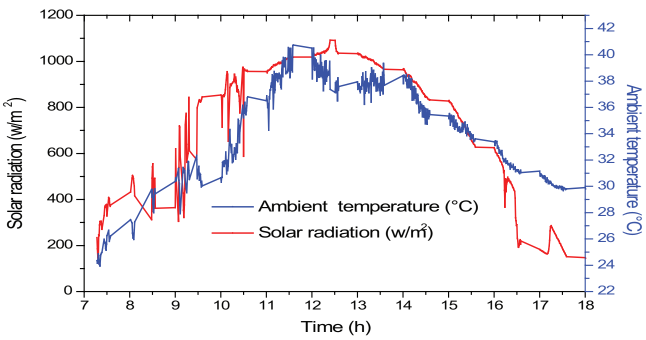

Fig. 3. Ambient temperature and solar irradiation measured during a typical day (17/08/2015).

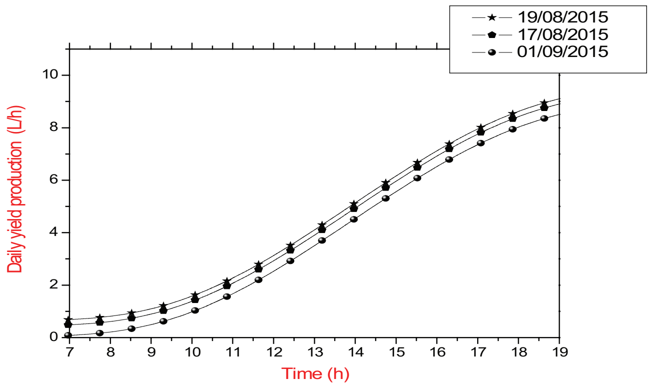

Fig. 5. Daily yield production of solar distiller vs. time for different days.

to study the low water depths in the solar distiller to increase the production of distilled water. Moreover, the lowest feedwater flow rate from the preheater gives a minimum depth of water film moving over the stepped surface of the new concept of solar distiller, which gives a maximum surface water temperature and subsequently improves the evaporation and the condensation process.

The influence of the inlet feedwater flow rate and temperature of the distillated water of the solar still unit is presented in Fig. 7. It is clear, therefore, that freshwater increase when the inlet water temperature rises. As a result, the increase of the inlet water temperature at the humidifier accelerates the evaporation process causing a lot of vapor and humid air which are transported to the tower of condensation where it comes into contact with the surface temperature lower than the dew point of the humid air thus improving the yield productivity.

Fig. 8 presents a comparative study of the performance of conventional solar still in this work at 1 cm depth. It is clear, therefore, that the freshwater and the hourly efficiency of the optimized solar still is higher than those of the conventional solar still for the same climatic conditions of Tunisia. Because we have added to this latter a flat plate solar collector to increase the temperature gradient between the water and the glass cover. Moreover, this is due to the addition of a plane air solar collector coupled with the humidifier to ameliorate the flow rate of the evaporated water and an inner condensation chamber in the optimized solar still system where condensation is produced at a temperature below that of the glass cover. From the graphs, it is clear that the thermal efficiency shoots up at 17:00 h because the value of solar radiation is very low.

4.4. Solar still temperature

Similarly, Fig. 9 shows the daily variations in temperature of the basin, water, ambient, and the glass cover for the optimized solar distiller unit during typical day except in the evening, which is also due to a higher thermal capacity of the basin water mass. During this day, the first thing that can be drawn from Fig. 9 is that all the temperatures showed a similar trend of increasing with the respective increasing of solar radiation on a sunny day. This figure also indicates that solar irradiation has a greater influence on the thermal

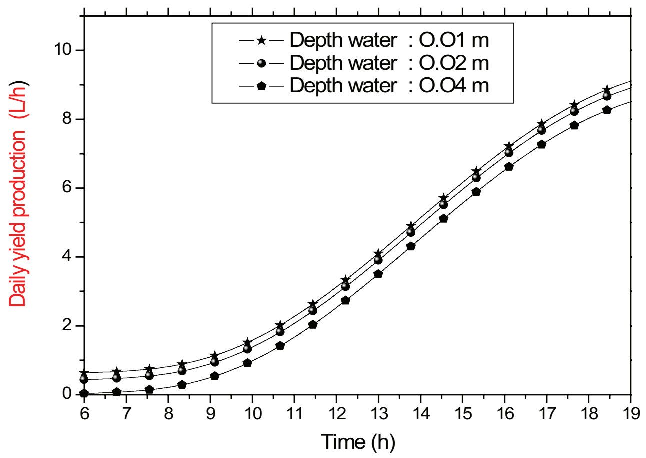

Fig. 6. Daily yield production of solar distiller vs. time for different depths of water.

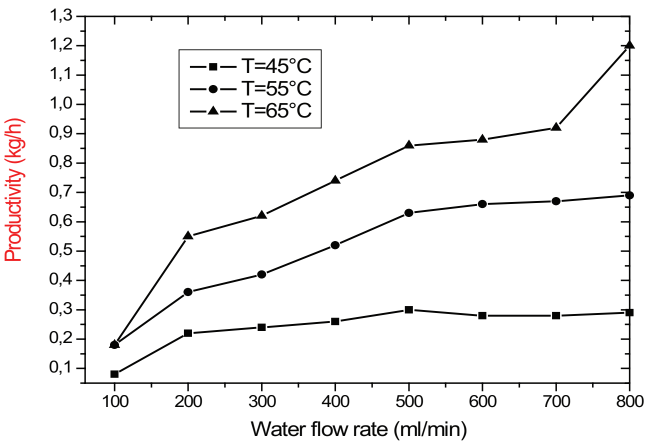

Fig. 7. Influence of inlet feedwater flow rate and temperature on the yield productivity of the solar still.

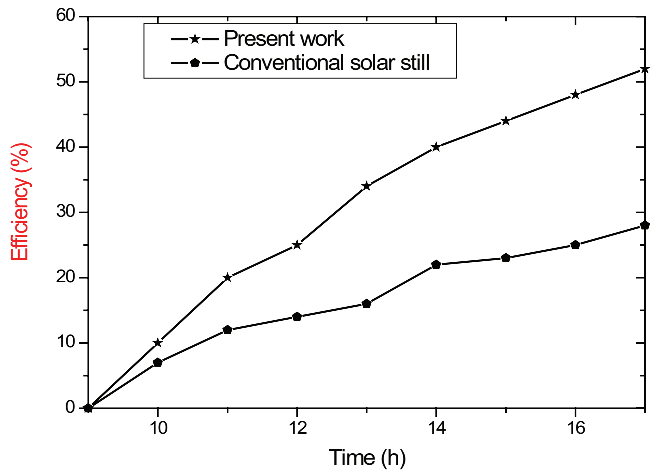

Fig. 8. Hourly variation of thermal efficiency for the two types of solar still.

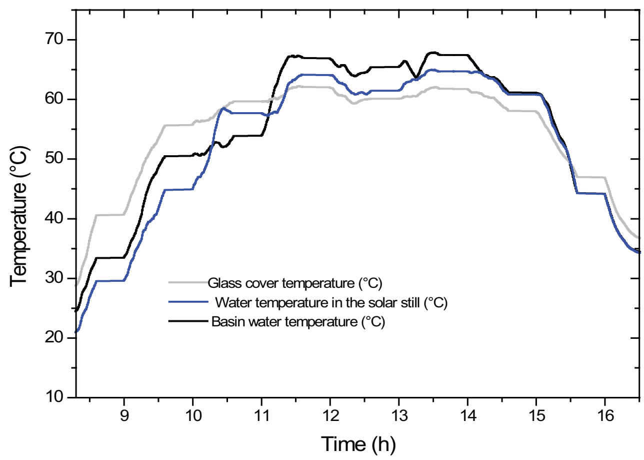

Fig. 9. Hourly variation of various temperatures of the solar distiller at local time (19.08.2015).

performance of the optimized solar distiller. The curves proportionally increase at the beginning of the day, reach a maximum values between 13 and 14 h, and then gradually decrease. It is also observed that the ambient and the water temperature of the solar distiller are the same due to the contact with the last two heat transfers by directly convection. The basin temperature reaches a maximum value of 67°C. The temperature of the optimized solar distiller reaches a temperature of 66°C; the temperature is also due to the effect of the preheater (water solar collector) and black absorber with the aim of increasing the heat exchange surface and absorption of the radiation. The maximum solar radiation value, which is shown in this figure, is recorded between 12–13 h, while the glass cover temperature (25°C–45°C) and the basin water temperature (67°C) reach their maximum values after 14 h, then the temperature of the glass cover begins to decrease as a result of the decrease of the amount of solar radiation falling on the solar still system in the sunset.

4.5. Air and water solar collector outlet temperature

On the basis of observations taken on solar still coupled with water and air solar heater, a graph is drawn, as presented in Figs. 10 and 11. In fact, these figures showed the temporal variations of air and water outlet temperature for a sunny day in August (19/08/2015) in the indicated weather conditions (solar radiation and air ambient temperature). The height values of air and water outlet temperatures are recorded between 12 and 13 h, while at ambient temperatures (20°C–40°C) after 16 h all temperatures begin to decrease as a result of the decreasing amount of solar radiation on the solar still system in the sunset. On the other hand, the water inlet and outlet temperatures and the outlet air temperature exactly follow the behavior of the solar radiation; this time delay represents the response time of the collector heater. Moreover, the inlet air temperature presents a small change in the way that the outlet water temperature of the water solar heater (80°C) is much higher than that of air solar heater (71°C). This result means that the water solar heater is more efficient than the air solar one. This may also be due to the thermal properties of water. The plane air solar collector consists of a blacked absorber-shaped like rectangular parallel channels consisting of copper, glass cover, and insulation. For the air solar heater, the model is based on Nafey et al.'s [20] work.

Fig. 12 shows the influence of water flow on the evolution of the outlet water temperature of the solar heater in the indicated weather conditions (solar radiation and air ambient temperature). This figure indicates that the outlet water temperature of the solar collector decreases when the flow rate of the water flowing through the solar water heater increases. So it is better to work with a low water flow rate to increase the outlet water temperature in the outlet of solar water collector.

4.6. Experimental parametric study of the humidifier

The variations of relative humidity (RH) at the inlet and the outlet of the humidifier are presented in Fig. 13. The maximum solar radiation value shown in this figure is recorded between 12 and 13 h, while the RH in the outlet of the humidifier (46%–60%) and the RH in the inlet of the humidifier (10%–20%) begin to decrease as a result of the absence of humid air. In the presented climatic conditions, the water and air temperature begins to increase from the morning till noon, while the inlet RH of the humid air decreases due to sensible heating of the humid air by air solar heater device output. Besides, the inlet RH of the humid air increases due to sensible heating of the moist air by solar irradiation in the afternoon. In fact, heating air by air solar heater decreases its

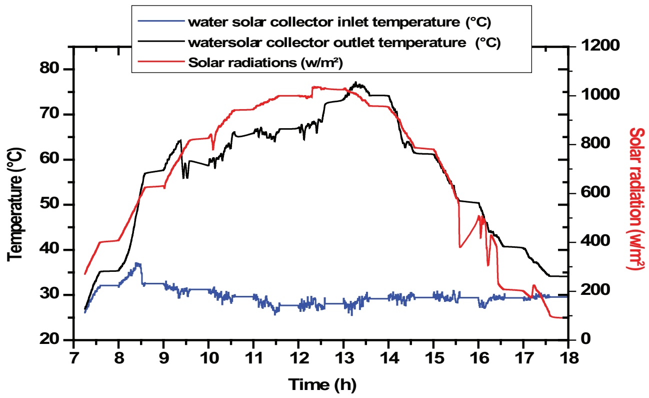

Fig. 10. Temporal variations of solar radiations, ambient temperature, and water solar collector outlet and inlet temperature during the day (19.08.2015).

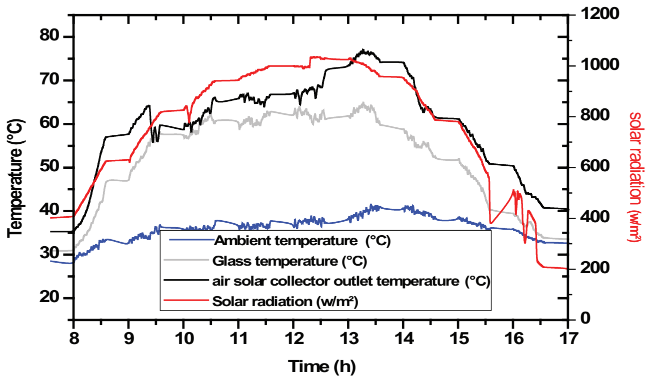

Fig. 11. Temporal variations of solar radiations, ambient temperature, and air outlet temperature in the solar air heater during the day (19.08.2015).

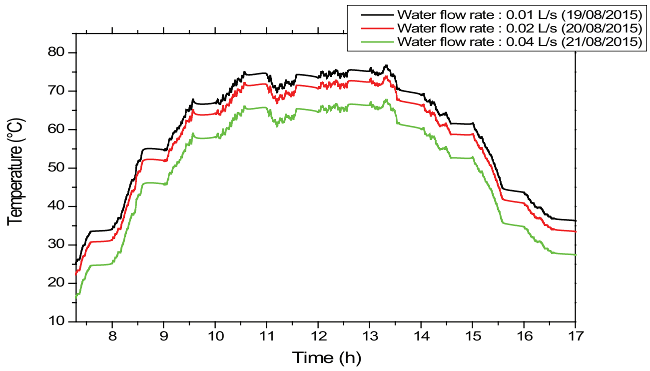

Fig. 12. Evolution of the water temperature at the outlet of the water solar heater for different water flows during various days.

RH, which in turn leads to the improvement of the capacity of air to load water vapor by subsequent humidification of air in the humidifier. This can be also confirmed using the psychometric chart of moist air. We can conclude that the performance of the humidifier chamber, which is connected to the solar distiller unit increases with the increase of the inlet RH and vice versa.

Table 3 presents a comparative study of solar distillers. It can be seen that the yield production of our optimized solar still system connected to a condensation chamber, water and air solar heater, and a humidifier is higher than the yield productivity of other solar still systems existing in the literature. This yield productivity is significant; it varies from 4 to 10.5 kg/m^2.d updated throughout the year. In this study, the addition of the inner condenser, humidifier, water solar heater, and air solar heater to the conventional solar distiller has an effect on the produced distilled water. This may be due to the humidification–dehumidification processes.

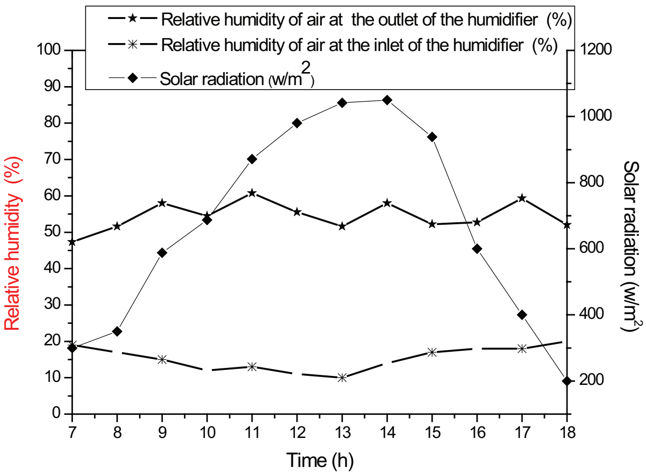

Fig. 13. Relative humidity at the outlet and the inlet of the humidifier chamber on 19/08/2015.

Table 3
Comparative study of solar distillers' yield productivity

Type of distiller	Wind speed	Ambient temperature (°C)	Location (latitude)	Authors	Production (kg/m^2/day)
Spherical distiller	2	25–30	Alger 36.833 36°49′N	Chaker and Menguy [21]	4–7
A weir-type cascade solar still	0–9	25–33	Zahedan, Iran (29.5°N)	Tabrizi et al. [22]	5.1
A solar still augmented with a flat-plate collector	_	18–25	Amman, Jordan (31.6°N)	Badran and Al-Tahaineh [23]	~2.3
A passive solar still with a separate condenser	2	20–28	Glasgow, UK (55.5°N)	Madhlopa and Jonstone [24]	~6.0
A single-basin double-slope solar still with energy storing materials	0.2–1.2	20–27	Tamil Nadu, India (11.2°N)	Murugavel et al. [25]	~2.1
A solar still with energy storage medium—jute cloth	_	11–22	Fukuoka, Japan (33.2°N)	Sakthivel et al. [26]	~4.0
Distiller coupled to a condenser, solar air and water collector and packed bed	1	20–30	Sfax 34°44′26″N	Present work	4–10.5

5. Economic analysis

The principal objective of the solar still unit is to minimize the cost production per liter of freshwater. Economic analysis is used to estimate the solar still cost because it may be technically very efficient. The economic analysis of the solar still is used to show both the payback period of the experimental setup and the cost of the produced freshwater. Table 4 summarizes the cost of each component of the optimized solar still. The payback period of the experimental application of the solar still unit is affected by the cost of reparation and construction. The total fixed cost of the solar still system of all components of the optimized solar still is €2300. In addition, the life time for a solar still unit is about 20 years.

The yield productivity of the solar still unit is 10.5 L/m^2.d updated throughout the 10 months.

The number of liters that would be produced from the solar still unit as the following:

The number of liters = 10.5 L/d × 300 d/y × 20 = 63,000 L
The cost of water per 1 L = 2,300/63,000 = €0.03/L
The cost of freshwater for 1 d = 0.03 × 10.5 = €0.315/d
The reparation cost = €0.01/d; net earning = 0.315–0.01 = €0.305
The payback period = 2,300/0.305 = 7,540 d

Table 4
Investment cost of each component of the optimized solar still

Components of solar still unit	Cost (€)
Solar still	500
Water solar collector	200
Air solar collector	200
Humidifier	650
Ducts	500
Immersed pump	100
Fan	150

6. Conclusions

In this work, the experimental parametric study of the optimized solar still connected to a condenser chamber, water and air solar heater, and humidifier chamber is designed, manufactured, and experimentally tested during daytime on a topical day in the city of Sfax in Tunisian climatic conditions. The newly designed system presented in this work shows a number of attractive attributes that might open new promising opportunities for the advent of freshwater to environments with limited water resources and high solar irradiation rates. Based on the obtained results, the following conclusions can be drawn:

- The various temperatures of the outside glass cover, basin of the solar distiller, ambient, and water and air temperature of the stills are recorded by using thermocouples, and the data are plotted.
- Thermocouples are located in the outlet and the inlet of the solar distiller unit and in the water and air solar collectors. Indeed, the yield productivity of our distiller increases with the decrease of the water depth in the blacked basin of the optimized solar still.
- Decreasing the inlet water temperature to the condenser of optimized solar distiller leads to the increase of the yield productivity. The solar intensity shows a similar variation during the days of the analysis.
- The lowest feedwater flow rate gives a minimum depth of water in the blacked basin of the optimized solar distiller and hence gives a maximum surface water temperature and subsequently improves the evaporation and the condensation process.
- It is found that the geographical location may have a positive effect on the increased water yield of the optimized solar distiller, especially for those locations with climatic weather conditions (solar radiation and air ambient temperature).
- The concept of using the preheater (water solar collector) is found to be a very attractive method to obtain freshwater. Because it improves the evaporation process. The periodic evolution of the solar radiation for the days of analysis is also plotted. The average value shows a similar variation on these days.

Symbols

C_w — Water heat capacity in the solar water collector, J/(kg.K)
C_b — Basin heat capacity, J/(kg.K)
C_v — Glass cover heat capacity, J/(kg.K)
m_w — Water mass flow sprayed onto the solar distiller, kg/s
M_a — Air mass flow density in the solar still, kg/(m^2.s)
M_v — Glass cover weight, kg
M_w — Water weight in the solar still, kg
M_b — Absorber weight of solar water, kg
T_b — Temperature of the absorber basin solar still, °C
T_v — Glass cover temperature of the solar still, °C
T_{amb} — Ambient temperature, °C
T_w — Water temperature in the solar distiller, °C
d_w — Water depth, m
p_w — Vapor pressure at T_w, atm
p_v — Vapor pressure at T_v, atm
V_{wind} — Wind speed

Greek

ε_{eff} — Effective emissivity
λ_o — Latent heat of water evaporation, J/kg
ε_1, ε_2 — Are, respectively, the emissivity of the absorber and the glass cover
ε — The emissivity
σ — Stefan–Boltzmann constant
ε_e — Water emissivity
ε_v — Glass cover emissivity

Subscripts

amb — Ambient
a — Air
w — Water
v — Glass cover
b — Basin

References

[1] M.M. Naim, M.A. AbdElKawi, Nonconventional solar stills Part 2. Non-conventional solar stills with charcoal particles as absorber medium, Desalination, 153 (2002) 71–80.

[2] A.K. Bassam, R. Himzeh, Experimental study of a solar still with sponge cubes in basin, Energy Convers. Manage., 44 (2003) 1411–1418

[3] Kalidasa Murugavel, K., Sridhar, K., Performance study on basin type double slope solar still with different wick materials and minimum mass of water, Renewable Energy, 36 (2011) 612–620.

[4] Y.P. Yadav, S.K. Yadav, Parametric studies on the transient performance of a high temperature solar distillation system, Desalination, 170 (2004) 251–262.

[5] H. Tanaka, Y. Nakatake, Effect of inclination of external flat plate reflector of basin type still in winter, Sol. Energy, 81 (2007) 1035–42.

[6] G.M. Zaki, A. Al-Turki, M. AI-Fatani, Experimental investigation on concentrator assisted solar stills, Sol. Energy, 11 (1992) 193–199.

[7] A. Ahsan, T. Fukuhara, Mass and heat transfer model of tubular solar still, Sol. Energy, 84 (2010) 1147–1156.

[8] 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.

[9] M.A. Eltawil, Z. Zhengming, Wind turbine-inclined still collector integration with solar still for brackish water desalination, Desalination, 249 (2009) 490–497.

[10] M. Arslan, Experimental investigation of still performance for different active solar still designs under closed cycle mode, Desalination, 307 (2012) 9–19.

[11] A. Kaushal, Varun, Solar stills: a review, Renewable Sustainable Energy Rev., 14 (2010) 446–453.

[12] A.M. El-Zahaby, A.E. Kabeel, A.I. Bakry, S.A. El-Agouz, O.M. Hawam, Augmentation of solar still performance using flash evaporation, Desalination, 257 (2010) 58–65.

[13] S.A. Zeinab, L. Ashraf, Improving the performance of solar desalination systems, Renewable Energy, 30 (2005) 1955–1971.

[14] G.N. Tiwari, J.K. Yadav, D.B. Singh, I.M. Al-Helal, A.M. Abdel-Ghany, Exergoeconomic and enviroeconomic analyses of partially covered photovoltaic flat plate collector active solar distillation system, Desalination, 367 (2015) 186–196.

[15] M.R.K. Estahbanati, M. Feilizadeh, K. Jafarpur, M. Feilizadeh, M.R. Rahimpour, Experimental investigation of a multi-effect active solar still: the effect of the number of stages, Appl. Energy, 137 (2015) 46–55.

[16] G.N. Tiwari, Lovedeep Sahota, Review on the energy and economic efficiencies of passive and active solar distillation systems, Desalination, 401 (2017) 151–179.
[17] H. Ben Bacha, K. Zhani, Contributing to the improvement of the production of solar still, Desal. Wat. Treat., 51 (2013) 1310–1318.
[18] K. Zarzoum, K. Zhani, H. Ben Bacha, Improving the design, modeling and simulation in dynamic mode of a solar still, Desal. Wat. Treat., 52 (2014) 6304–6314.
[19] K. Zarzoum, K. Zhani, H. Ben Bacha, Numerical study of a water distillation system using solar energy, J. Mech. Sci. Technol., 30 (2016) 889–902.
[20] A.S. Nafey, M. Abdelkader, A. Abdelmotalip, A.A. Mabrouk, Solar still productivity enhancement, Energy Convers. Manage., 42 (2001) 1401–1408.
[21] A. Chaker, G. Menguy, Efficacité interne d'un distillateur solaire sphérique, Rev. Energ. Ren. Thermal Days, (2001) 53–28.
[22] F.F. Tabrizi, M. Dashtban, H. Moghaddam, Experimental investigation of a weir-type cascade solar still with built-in latent heat thermal energy storage system, Desalination, 260 (2010) 248–253.
[23] O.O. Badran, H.A. Al-Tahaineh, The effect of coupling a flat-plate collector on the solar still productivity, Desalination, 183 (2005) 137–142.
[24] A. Madhlopa, C. Jonstone, Numerical study of a passive solar still with separate condenser, Renew. Energy, 34 (2009) 1668–1677.
[25] K.K. Murugavel, S. Sivakumar, J. Riaz Ahamed, Kn.K.S.K. Chockalingam, K. Srithar, Single basin double slope solar still with minimum basin depth and energy storing materials, Appl. Energy, 87 (2010) 514–523.
[26] 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.