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Innovation of Solar Desalination System Coupled with Solar Collector: Experimental Study

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ABSTRACT

The supply of drinking water is a growing problem especially for developing countries because of the industrial development, intensified agriculture, improvement of standard of life and increase of the world population. For this reason, purification of water supplies is extremely important. Solar stills are used for solar distillation plants due to its simplicity in construction and operation, low cost and however the yield is low. Because of its low productivity it is not popularly used. A lot of research work is undertaken to improve the productivity of the still. This paper presents the new design of solar distillation system coupled to a condenser, solar air and water collector and packed bed. This new concept of distiller solar still using humidification-dehumidification processes which is exploited for the desalination purpose. The experiment is carried out during the summer climatic conditions of Tunisia. The productivity in a solar still mainly depends on the temperature difference between the evaporation tower water and the condensation tower for a given surface area. The results clearly show that the instantaneous efficiency increases with the increase of solar radiation and with the increase of feed water temperature.

Keywords:
Solar still; humidification; dehumidification; experimental investigation; desalination; condensation; evaporation

1.Introduction

Water and energy are the two basic elements that influence the quality of civilized life. Fresh water is the fundamental life source on earth. Today, fresh water demand is increasing continuously because of the industrial development, intensified agriculture, improvement of standard of life and increase of the world population. The rapidly increasing need for energy and environmental concerns has focused much attention on renewable energy resources [1]. Water is

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an abundant natural resource that covers three quarters of the earth's surface. However, around 97% of the water in the world is in the ocean, only about 3% of all water sources are potable.

Less than 1% fresh water is available within human reach and even this small fraction (ground water, lakes and rivers) is believed to be adequate to support life and vegetation on the earth and the rest is permanent snow cover, ice and permafrost in Polar Regions [2]. Large quantities of fresh water are required in many parts of the world for agricultural, industrial and domestic uses. The utilization of renewable energy offers a wide range of exceptional benefits and expected to have a flourishing future and an important role in the domain of brackish and seawater desalination in developing countries [3]. Fortunately, the regions in most need of additional fresh water are those with the most intense solar radiation. For this reason, thermal solar energy in desalination processes should be the most promising application of renewable energies to seawater desalination [4]. Solar distillation systems can be small or large. It was manufactured for the production of between 10 to 40 liters of drinking water per day which meets the needs of a single family. In some parts of the world the scarcity of fresh water is partially overcome by covering shallow salt-water basins with glass in greenhouse- like structures. These solar energy distilling plants are relatively inexpensive, low technology systems, especially useful where the need for small plants exists [5]. Most stills built and studies since then have been based on the same principles, though many variations in geometry, materials, methods of construction, and operation have been incorporated [6,7]. Kalidasa, Murugavel and Sritharhave conducted experiments for the still up to a minimum depth of water and different wick materials like light cotton cloth, sponge sheet, coir mate and waste cotton pieces, and aluminum rectangular fin arranged in different configurations in the basin. The cost of building and operating a conventional still is relatively low compared to those involving sophisticated designs. However, the conventional or standard basin type solar still [8,9] proven to have a low thermal efficiency with low daily distillate productivity [10]. The efficiency and yield of the conventional solar still depend on different factors: the design and functionality of the still, location, weather conditions, etc. [8]. Their low thermal efficiency is due to the considerable shadow caused by the walls of the basin that tend to decrease the absorption of solar radiation that could have been used for water distillation process. In order to improve the performance of conventional solar stills, several other designs have been developed, such as the double-basin type [11], multi-basin [9-12], inverted trickle [13], multi-effect [14], regenerative [15], with reflectors [16]. Kalogirou [17] presented an excellent review on various types of passive and active solar stills. Among these types are the single-slope with passive condenser, double condensing chamber solar still, vertical solar, and conical solar still. In this paper, a modification in design of a single slope solar still is presented and its performance is evaluated in Allahabad climatic condition. The condensing cover made-up of glass cover is replaced with a PVC material. Sampathkumar *et al.,* [18] have made an attempt to investigate a newly deign solar still coupled with an evacuated tube collector experimentally. It was found that the maximum productivity of the still is increased when coupled with evacuated tube collector. The maximum production rate of the solar still coupled with and without evacuated tube collector is found to be 7.03Kg/day and 3.225Kg/day. Sampathkumar *et al.,*[19] have studied the performance of the single basin solar still augmented with evacuated tubes and inferred that the daily production rate of the solar still is increased by 49.7% and increased by 59.48% by using black stones incorporated with evacuated tubes. Rajaseenivasan *et al.,* [20] have used various different wick and porous materials like black cotton cloth, jute cloth, waste cotton pieces, clay pots facing up and down and mild steel pieces in double basin and single basin solar still. They found double basin solar still with mild steel plates found more productive compared with other materials. Shanmugana *et al.,* fabricated single slope basin type solar still is provided with a dripping system to pour saline water drop by drop in the basin by using 4 mm glass cover thickness. Thermal modeling and analytical solution have been valued in the temperature of glass cover water and watershed. By Using of 4 mm glass cover thickness they found maximum output was 3.2 liter.

Maximum efficiency of still is found to be 40.58 % and 36.24 % in summer and winter days respectively [21]. Gajendra Singh [22] designed HPVT double slope active solar still for their performance on the substantiation of actual modeling. Some of the parameters measured as solar intensity, ambient temperature, water temperature inside still, inner & outer surface temperature of a glass cover, they measured the coefficient of correlation varying from 0.872 to 0.965. Omar Ansari [23] has described that the solar desalination system used brackish water in passive solar still with a heat energy system put under the basin liner of the desalination device. It shows the whole excess energy generated during sunshine time and stored in PCM for later use during night time and rainy day. Srivastava *et al.,* [24] developed a simple modification of single slope basin type solar still with consisted porous fins (black ended old cotton rags) inside the basin. The productivity of the distillate increases from February until May. The distillate productivity increases with the decrease in the basin water depth. Kannan, *et al.,* [25] designed and tested a vapor adsorption type solar still and the experimental and analytical results were compared to the energy equation for both conventional and vapor adsorption type solar still, hence found that theoretical results performed well with experimental results. Khalifa *et al.,* [26] valued correlation of solar still where the correlation shows the effect of productivity of brine depth, cover tilt angle and dye. The correlation values find the enhancement of value of the root means square to enhance the correlation experimentally. Omara *et al.,* [27] had taken various parameters like storage bed and water depth with different sand materials (yellow and black) used experimentally. It indicated that the heat storage sends enhanced productivity. Maximum productivity was achieved at sand bed heights of 0.01 m and above the sand bed layers to zero height of saline water compared to conventional style. Panchal *et al.,* [28] performed a single slope, solar still 2-phase; 3D model made for evaporation conduct a condensation process in still by using ANSYS CFX method. Proved that ANSYS CFX method is a powerful instrument to diagnose solar still. Kalidasa Murugavel *et al.,* [29] defined that inclined type solar still has a higher surface area and thin water surface. It revived that different methods use data improve the effectiveness of the inclined solar still and compared it the other's solar still performance [29]. Husham [30] explored different methods of discovering ways of solar still efficiently and maximum productivity still connected with different condensers condense the still to increase distillate output during any season, in regard to that produced by the conventional simple solar still, overnight production also found increases. Kabeel [31] performed an experiment about solar still with various parameters of glass cover and evaporative surface area. Average distillate productivity during the day time is approximately 12 L/m² with a system efficiency of 0.38 at solar noon. It is more eminent than the conventional type solar still. Patel *et al.,* [32] compared different solar stills which are stepwise basin solar still, pyramid solar still and concave/convex basin solar still,due to different designs of solar still, its parameter changes and to find out that which one is the bestest designs compare to others. Bacha *et al.,* [33] designed a new solar still with an energy storing material, where in the basin, a flat plate solar collector and a separate condenser that coupled with the solar still to increase the daily productivity by increasing the temperature of the water during the day and to store the excess hot water that would extend water desalination beyond sunset. This work, experimental investigation on a new solar distillation system is carried out [34].

This paper is therefore an attempt to experimentally investigate the performance of a solar still at different water depths in the basin under the prevailing weather condition in Tunisia. The distilled water productivity, the water – basin temperature, vapor temperature air temperature and ambient temperature were measured. In our parts, to ameliorate the production of the solar still, we have added to this latter

- A flat plate solar collector to increase the temperature gradient between the water and the glass cover
- 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
- A plane air solar collector
- A separate condenser for the solar distiller where condensation is produced at a temperature below that of the glass cover

2. Material and Methods
2.1Design of the System

The apparatus shown in Figure 1(a)-(c) illustrates a schematic diagram of the experimental setup. Figure 2 and 3 show respectively a side and front views photograph of the experimental setup.Solar distillation system is useful especially in summer season when the solar radiation attends its high values. So, it is of interest to investigate the experimental behaviour of the modified solar still during summer season. Experimental measurements were carried out using the solar distillation prototype located at the National Engineering School of Sfax, Tunisia (34 N, 10 E) and tested on several sunny days. This system was built in the climatic conditions of city in Tunisia. Data obtained included environmental condition (solar intensity radiation, ambient temperature and humidity), design parameters (basin absorptivity), and operational procedure (initial saline water temperature, air temperature, glass cover temperature) indicated that these decisively influence the still performance. Energy collection is performed by means of the solar collector and of the solar distiller. A black rubber mat, placed at the bottom of the still was used to enhance the amount of solar energy absorbed within the system and, thus, increase the amount of distilled water produced. The glass cover of thickness 4 mm is used as the condensing surface.

The solar desalination system under study differs from the previously explored published works by using a humidifier, on the one hand, and a field of flat-plate air solar collector and a field of flat-plate water solar collector on the other, which makes the system more flexible and increases the fresh water production.

Sea or brackish water which is preheated in the condensation tower of the solar still, by the latent heat of condensation, and heated in the water solar collector is pulverized into the humidifier. Due to heat and mass transfers between the hot water and the heated air stream in the humidifier in case of working in open air loop and between the hot water and the dehumidified air stream, coming from the condensation tower in case of working in closed air loop, the latter is loaded by moisture. 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, and therefore to raise the rate of air humidification, packed bed is implanted in the tower of the humidifier. The saturated moist air is then transported toward the tower of condensation where it comes in contact with a surface the temperature of which is lower than the dew point of the moist air. The condensed water was collected from the bottom of the condensation tower of the solar still, while the brine (the salty water exiting the humidifier) at the bottom of the humidifier will be either recycled and combined with the feed solution at the entry point or rejected in case of increase of saltiness rates. The detailed descriptions of the solar still main components are as follows

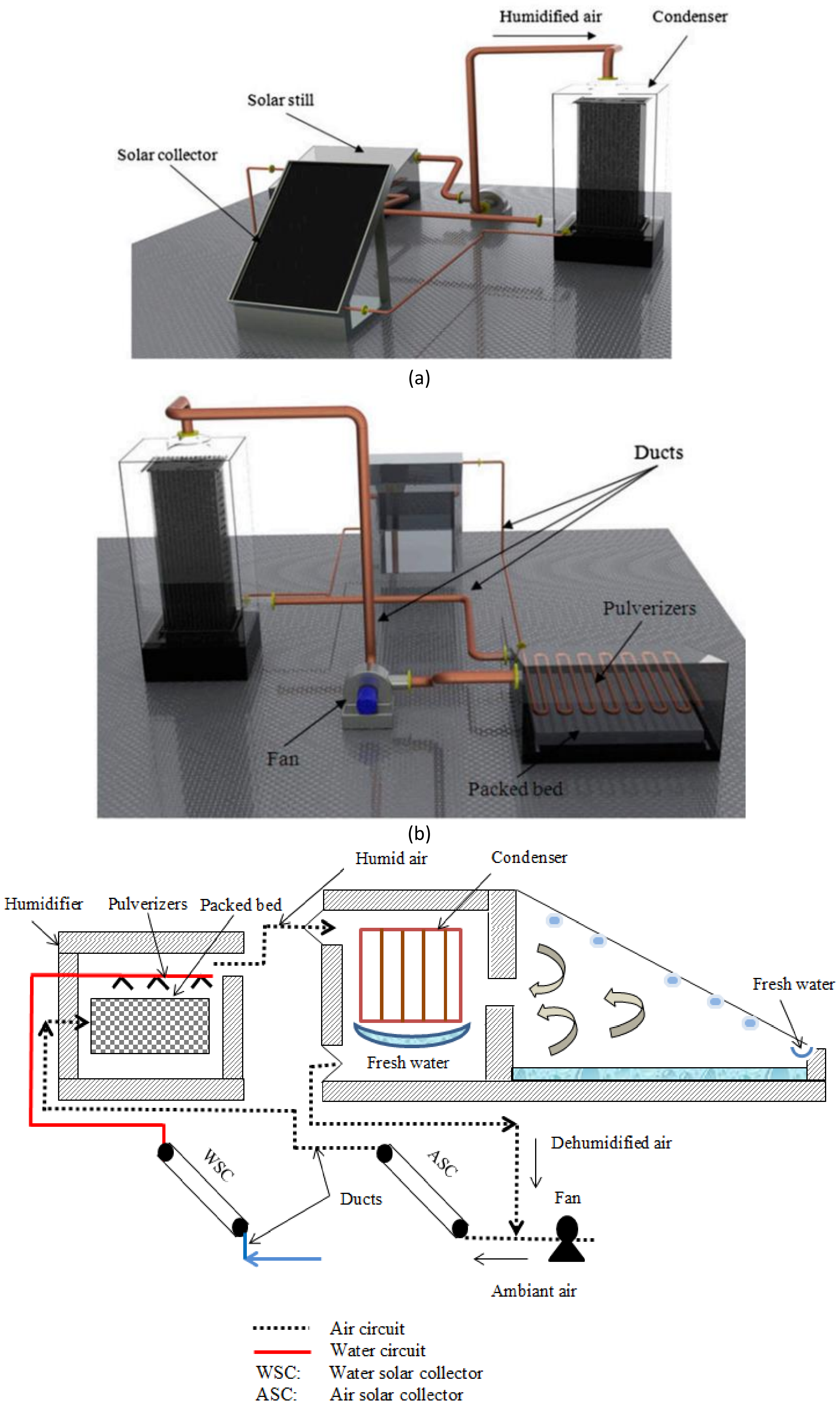

Fig. 1. (a) Front view, (b) back view and (c)a schematic diagram of the experimental setup

Most liquid collectors use a sheet-and-tube absorber with the tubes in front of, behind, or as an integral part of the sheet. The water solar collector device used by the present distillation prototype is composed of 2 collectors 2 m in length and 1 m in width. The water solar collector uses a sheet and tube, in copper material, absorber with the tubes as an integral part of the sheet, the inner diameter of the tubes is 10 mm and the outer one is 12 mm.

The air gap between the absorber and the glass cover is 0.1 m. The rear and sides insulations were provided by polyurethane to reduce heat loss. A silicon sealant was used between the different components of the water solar collector to ensure insulation from the environment.

The current solar distillation prototype employs 8 m^2 of air solar collectors which are connected in combination of parallel and series as shown in Figure 2. The air solar collector has 2 m length and 1 m width, and is formed by a single glass cover and an absorber.

The absorbing aluminum material that traps the energy was constituted of 20 separated rectangular channels with a thickness of 1 mm. The separating distance is 2 mm and each flow channel was 40 mm in a height.

The air gap between the absorber and the glass cover is 0.1 m. The rear and sides insulations were provided by polyurethane to reduce heat loss. A silicon sealant was used between the different components of the air solar collector to ensure insulation from the environment.

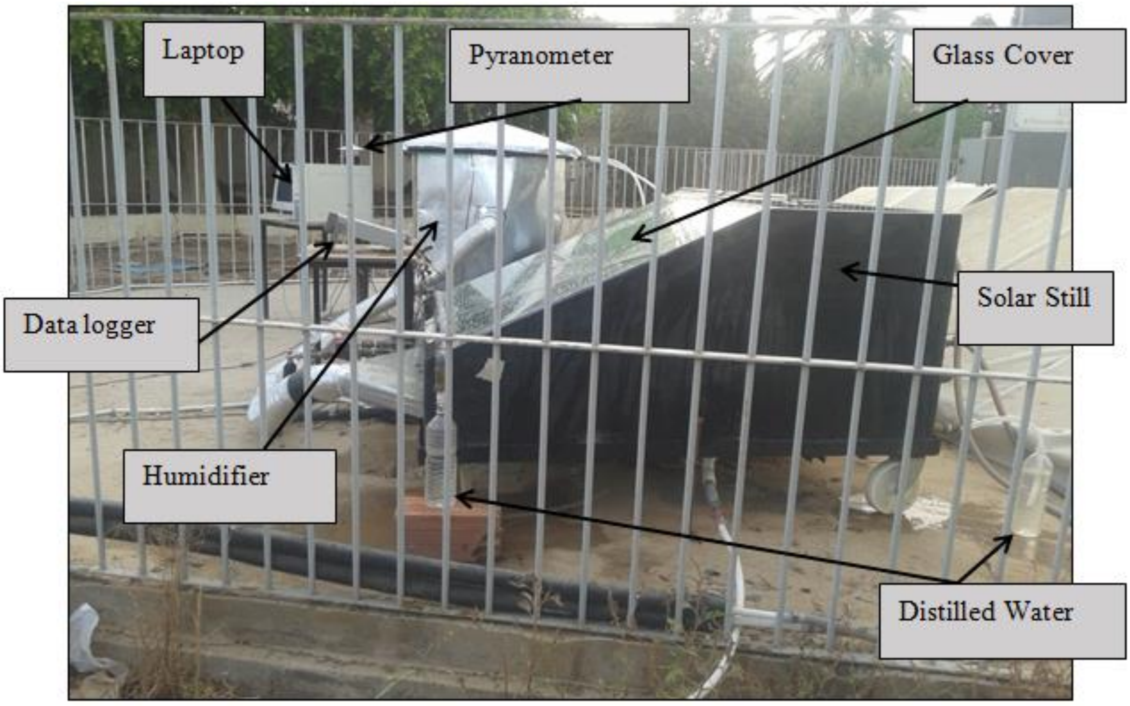

Fig. 2. Photograph of the experimental still (side view)

In order to achieve the maximum yield from the system, the still orientation should be the direction at which the highest average incident solar radiation is obtained. The operating principle of this system is as follows: the brackish water or the cold sea water returning in the condensation stage undergoes preheating by the latent heat of condensation.

Then, the water is heated in a solar water body; and atomizes in the form of small particles by means of high pressure atomizing nozzles or a compressed air nozzle or a piezoelectric transducer generating ultrasound. The water vaporizes in the still and is injected into the condensation stage to ensure the dehumidification of the vapor obtained. On the other hand, in the packed columns, the liquid is sprayed onto the packed bed between the grids. The liquid phase, which contains the absorbent, forms a film on the packing elements (wetting zone). The humidified air exiting the distiller will be conveyed to the condensation stage, where it condenses when it comes in contact with the outer walls of the tubes that circulate cold water. The amount of the condensed air (The distilled water) produced will be collected in a tray placed below the condensation chamber and on the inner surfaces of the glass cover. The condensation chamber was equipped with a ferry of a size 0.5 x 0.7 x 0.4 m to collect the produced fresh water. The latter was evacuated outside the solar still by an immersed water pump.

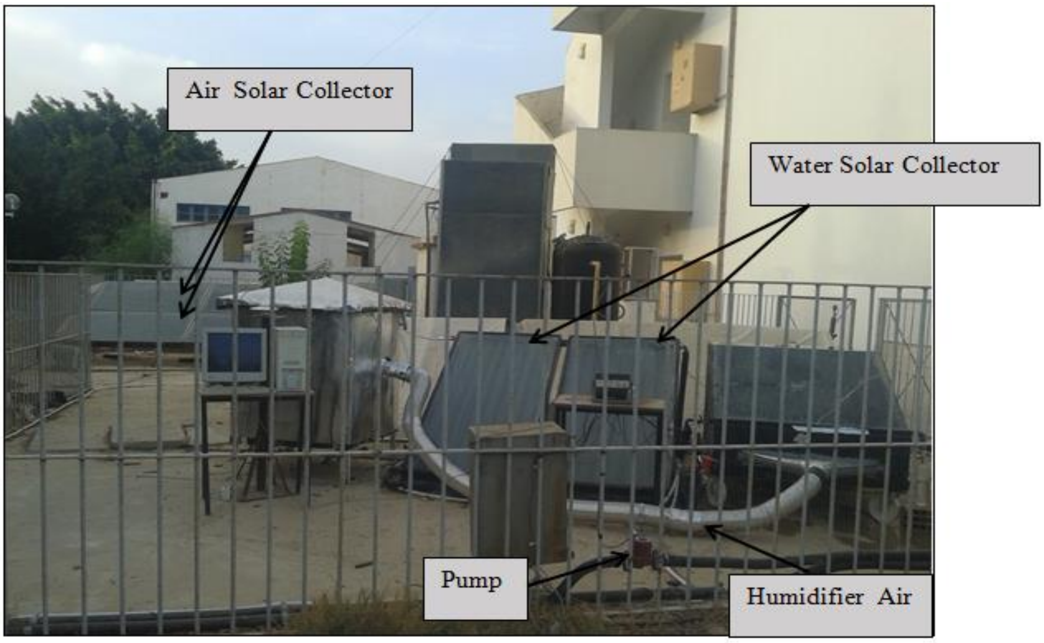

Fig. 3. Photograph of the experimental still (front view)

It runs along the lower edge of the glass cover. The amount of evaporated water that condenses will not be injected back to the solar distiller. The amount of evaporated water which is not condensed will be injected again to the solar still. The solar desalination system under study differs from the previously explored published works by using a humidifier, on the one hand, and a field of flat plate air solar collectors and a field of flat-plate water solar collectors on the other, which makes the system more flexible and increases the fresh water production. The humidifier used in the distillation prototype is a pad one is presented in Figure 4. The cross sectional area of the pad is 0.6 m x 0.8 m, while its height is 0.56 m. at the top, there is a liquid distributor, which can feed the pad with hot brackish water coming from water solar collectors, while at the bottom there is a liquid collector, where brine is collected as it drains down the pad.

Thus, the hot brackish water flows downward, while the air passes in a cross-flow direction. Textile (Viscose) of a 14 m^2 (52 m^2/m^3) surface is used as packing to increase the interface area between the air and water, which form the wetted surface. On the outside, the humidifier is covered with a polyethylene sheet of thickness 15 mm and insulated with a layer of armaflex.

The pyranometer is used to measure solar insolation with 1% accuracy and 12.29 $\mu V/Wm^2$ sensibility placed in a horizontal plane adjacent to the collector. Thermocouples were located in different places of the solar still and the water and air solar collectors. They record the different temperatures, such as outside glass cover, solar basin water, water and air temperature and ambient temperature [35].

Temperature sensors (thermocouples) measures temperatures and store the values in data logger. The data logger is connected with laptop hence readings were recorded in a laptop.

Temperature sensors having a least count of 0.1°C. Various thermocouples are attached to measure the temperature of particular place and connected with the overtime data recorder (Data Logger) that is simply fixed with some program software and plug in with computer. Computer records data with it and works during a sunny day. These thermocouples are mounted with logger and fixed with different channels, and indicates the channel wise simulation of temperature. Those channels are measured different input and output parameters. The view of channel and program run on computers are shown in Figure 2 and 3. A view of the condensing chamber and photograph of the experimental setup are shown in Figure 5.

Fig. 4. Humidifier used in the solar desalination system

Fig. 5. Photograph the condensing chamber and photograph of the experimental setup

3. Experimental Results and Discussion

The measured climatic conditions; solar radiation and ambient temperature for a typical two days in august (summer time) at the city of Sfax, Tunisia are presented respectively in Figure 6, 7 and 8. Those figures show an hourly variation of solar radiation and ambient temperature for various days (17/07/2020, 19/07/2020 and 01/08/2020). These days are characterized by clear sky conditions. One can observe that the maximum solar radiations are at 13:00 h for this tow experimental days then decreases. It is seen that during the day from sunrise to sunset, the solar radiation and ambient temperature increases gradually and reaches a maximum value at around noon period and then it decreases. Solar radiation and ambient temperature present meteorological conditions which affect on distiller performance.

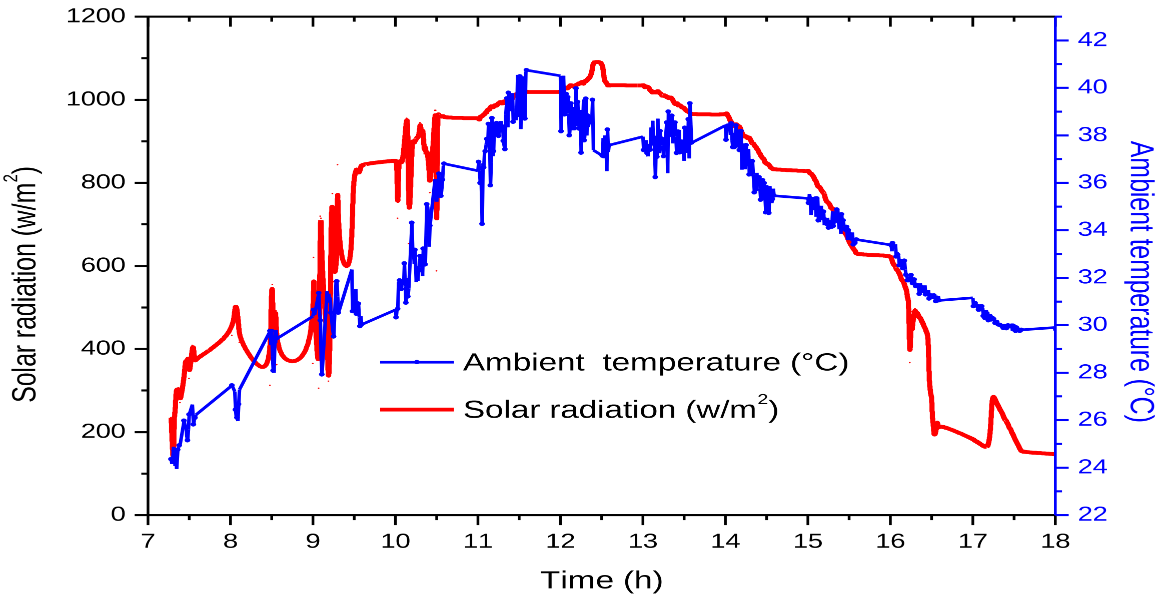

Fig. 6. Hourly variations of solar radiation and ambient temperature with local time (17.07.2020)

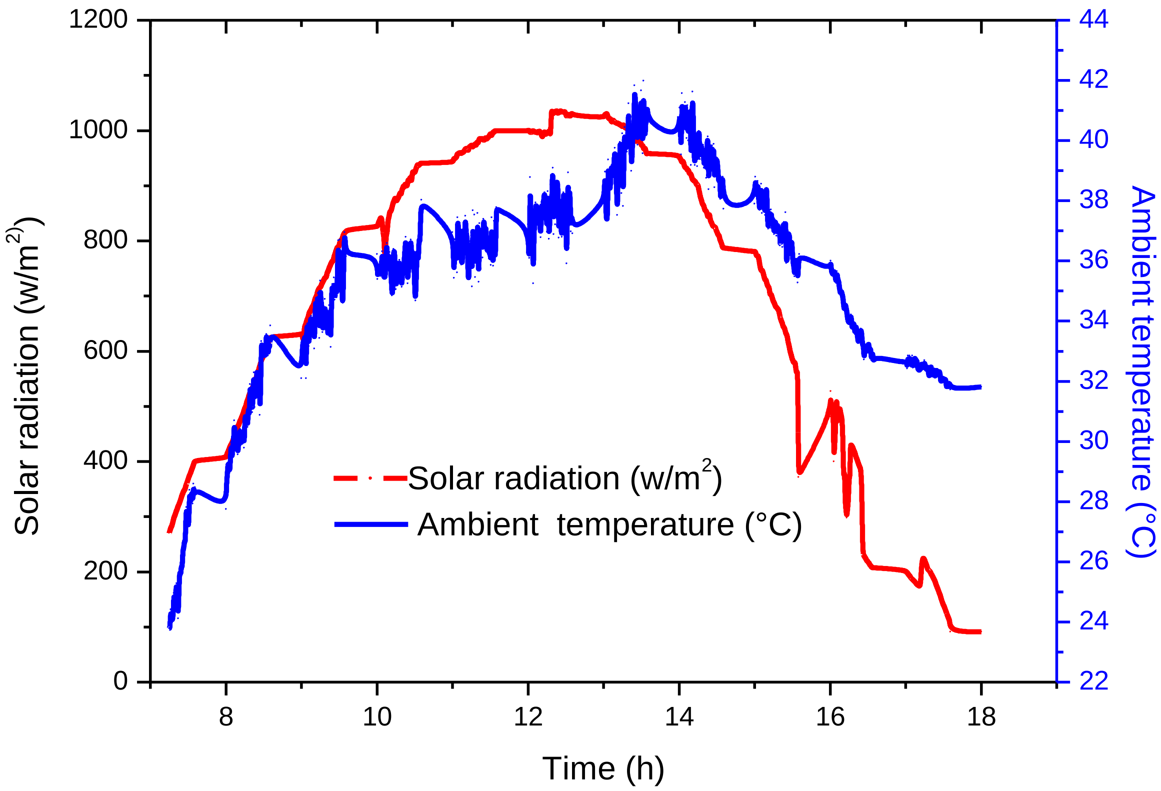

Fig. 7. Hourly variations of solar radiation and ambient temperature with local time (19.07.2020)

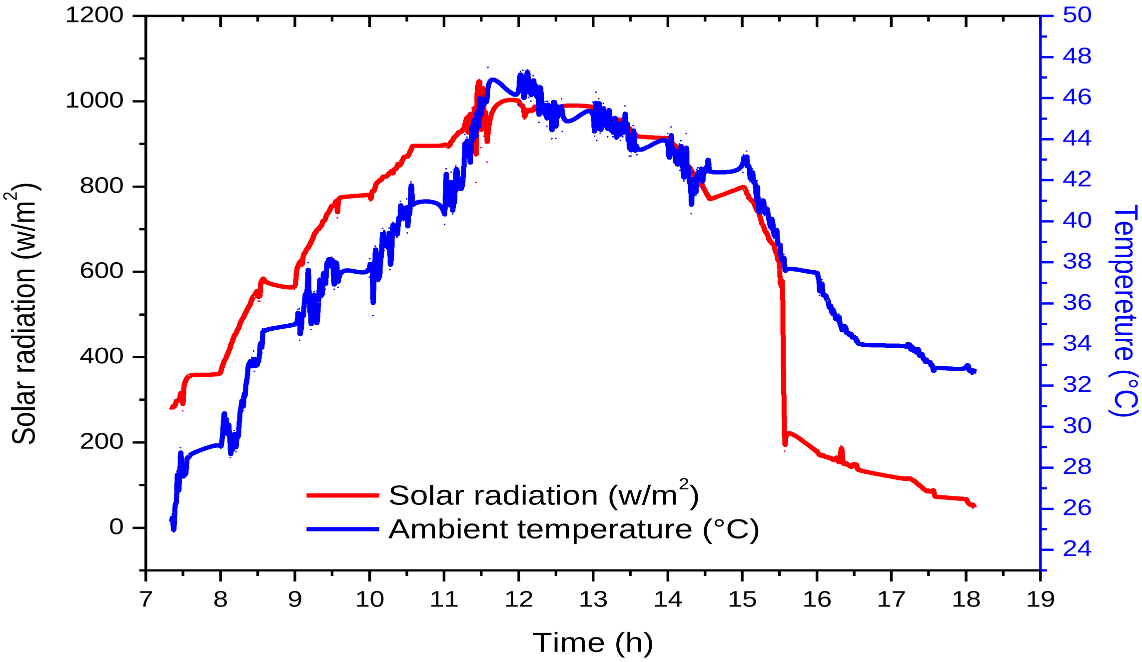

Fig. 8. Hourly variations of solar radiation and ambient temperature with local time (01.09.2020)

The temperature profiles for the basin, water, ambient and the glass cover for the modified solar still are shown in the Figure 9, Figure 10 and Figure 11 in function of time for the days August 17, 2020; August 19, 2020 and 01 September2020. The first thing that can draw from those tow figures that temperatures at all points increase with time till the maximum value at about 13 hour afternoon and then decrease again.

The second point is that the water temperature Tw and the absorber Tb (basin) are almost the same because of contact with the last two heat transfer by convection directly.

The curves increase gradually at the beginning of the day, reaching a maximum between 12h and 14h, then decreased gradually. The temperature of the absorber reaches a maximum value of 79 ° C for the day of August 17, 2020, of 80 ° C for the day of August 19, 2020 and of 77 ° C for the first day of the month of September 2020. This variation depends of the relative absorption coefficient of the solar water collector as a function of time.

The maximum solar flux value witch shown in those figures is recorded between (12-13) hours. While the ambient temperature (40°C - 45°C), the glass cover temperature Tg (50°C-53°C) and the basin water temperature 79 °C reach their maximum values and after 14 hours. The temperature of the glass cover begins to decrease as a result of decreasing the amount of solar radiation falling on the solar still a shadow effect due to a decrease of energy. The glass covers allow the solar radiation to pass through them and trap the solar energy inside the still. We note that the temperature of the glass (50°C - 53°C) is low compared to that of water (79 °C). Due to this process of evaporation, the salts and other bacteria are left behind in the basin while the water evaporates. This is explained by convective exchange with the ambient and the effect of the evaporator, which in turn allows the cooling blanket. This phenomenon allows water vapor to condense on the inside of the glass. When the condensate drops reaches its threshold size, they start flowing downward under the influence of gravity and the obtained distilled water is collected. It can be seen that a gradual increase in the water temperature occurs and reaches the maximum value in the afternoon period.

This is due to the increase in the absorbed solar radiation that exceeds the losses to the atmosphere. It can be seen that a gradual increase in the water temperature occurs and reaches the maximum value in the afternoon period. This is due to the increase in the absorbed solar radiation that exceeds the losses to the atmosphere.

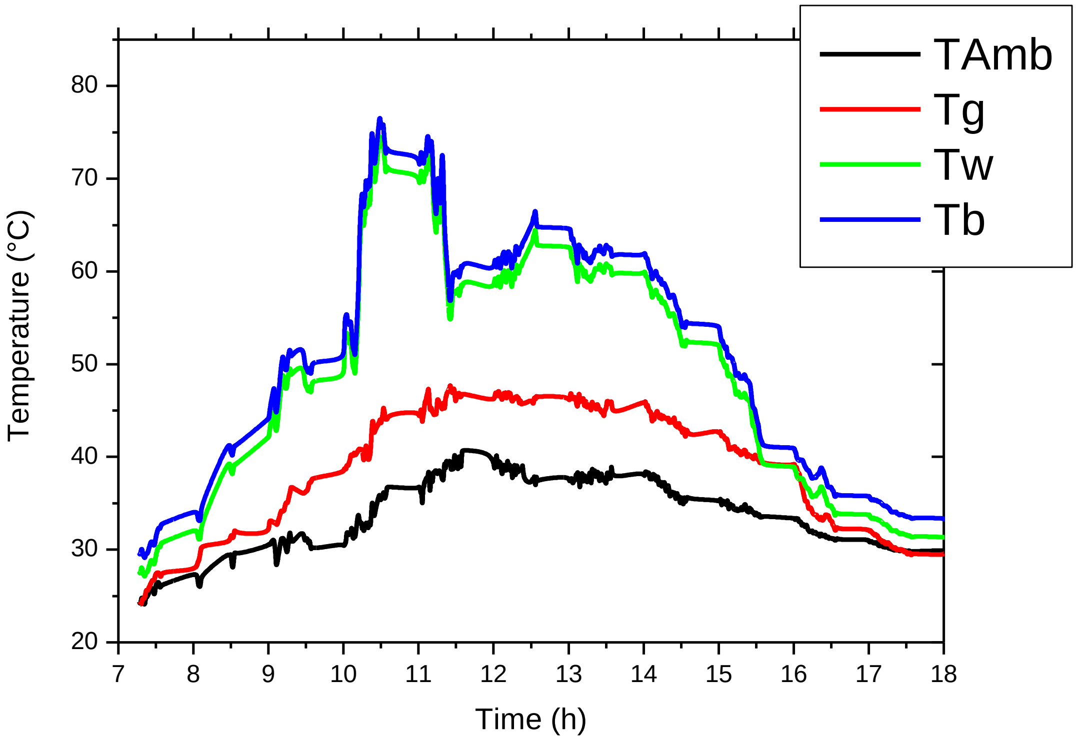

Fig. 9. Hourly variation of various temperatures of the solar still with local time (17.07.2020)

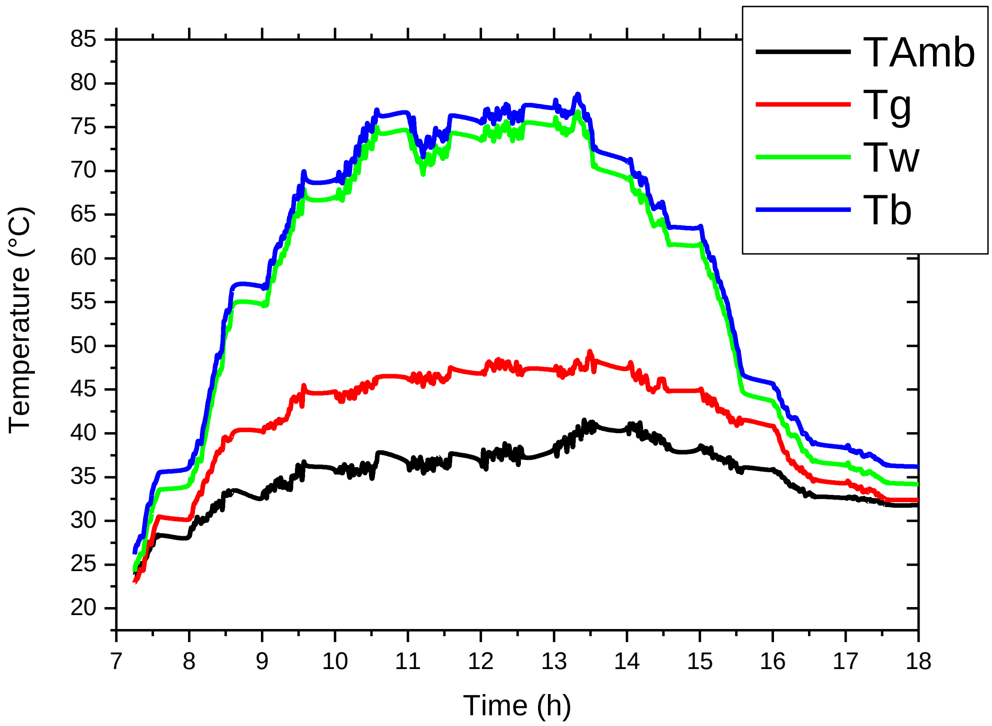

Fig. 10. Hourly variation of various temperatures of the solar still with local time (19.07.2020)

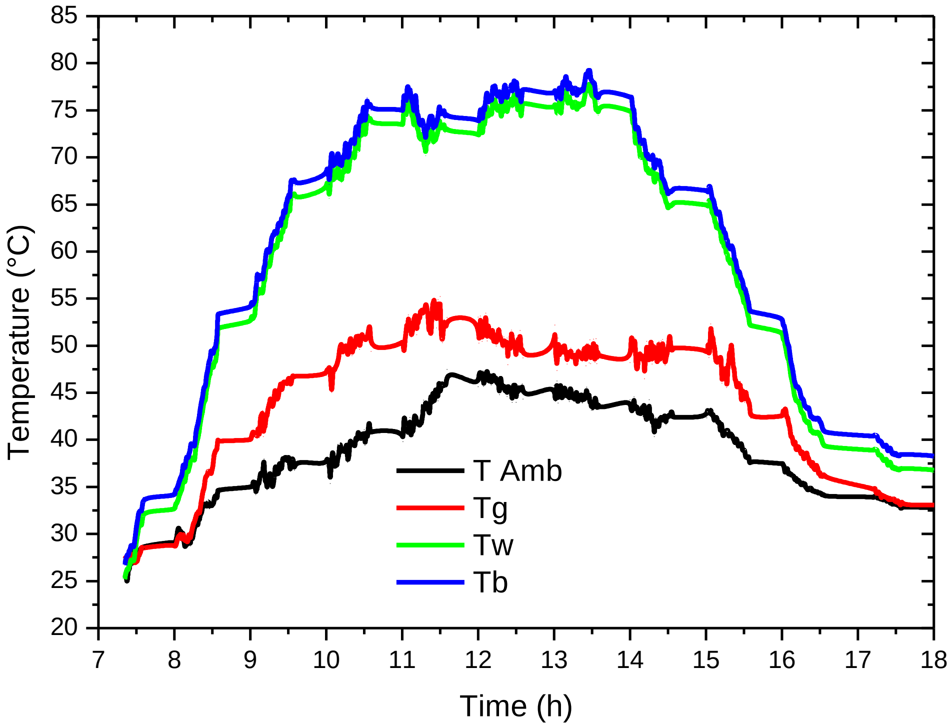

Fig. 11. Hourly variation of various temperatures of the solar still with local time (01.09.2020)

Hourly variations of solar radiation and water solar collector outlet temperature and of air solar collector outlet temperature are shown in the Figure 12-17 in function of time. Shows the response of the collector outlet temperature to natural fluctuation of solar radiation during daylight hours. In fact, it can be seen from those figures that when the solar radiation intensity presents a temporal fluctuation, a residual vacillation of the collector outlet temperature follows rapidly. It was noticed that air and water outlet temperatures exactly follow the behaviour of the solar radiation.

The maximum solar flux value witch shown in those figures is recorded between (12-13) hour, while the outlet air temperature (76 °C- 83 °C) and the outlet water temperature (75°C-77 °C) reach their maximum values and after 14 hour the tow temperatures begin decrease as a result of decreasing the amount of solar radiation falling on the solar still a shadow effect due to a decrease of energy.

Therefore, the collector presents a good response time to any climatic disturbance. On the other hand, the maximum values of both air and water outlet temperatures were obtained in between 12h and 14h, and then decreased gradually. It is clear from this figure that the temporal variations of water and air solar collector temperatures have the same trends as solar radiation. These results indicate that solar radiation has a greater influence on thermal performance of the water and air solar collector than the ambient air temperature. This would be useful to optimize the functioning of the water and air solar collector by integrating into it a regulation algorithm based on weather conditions.

For the high solar radiation intensity, the better response time of the air solar collector leads to an increase in the thermal performance of the air solar collector and then the production of the solar still. But for low solar radiation intensity, the rapid response of the collector to solar fluctuations may be deficiency for solar still.

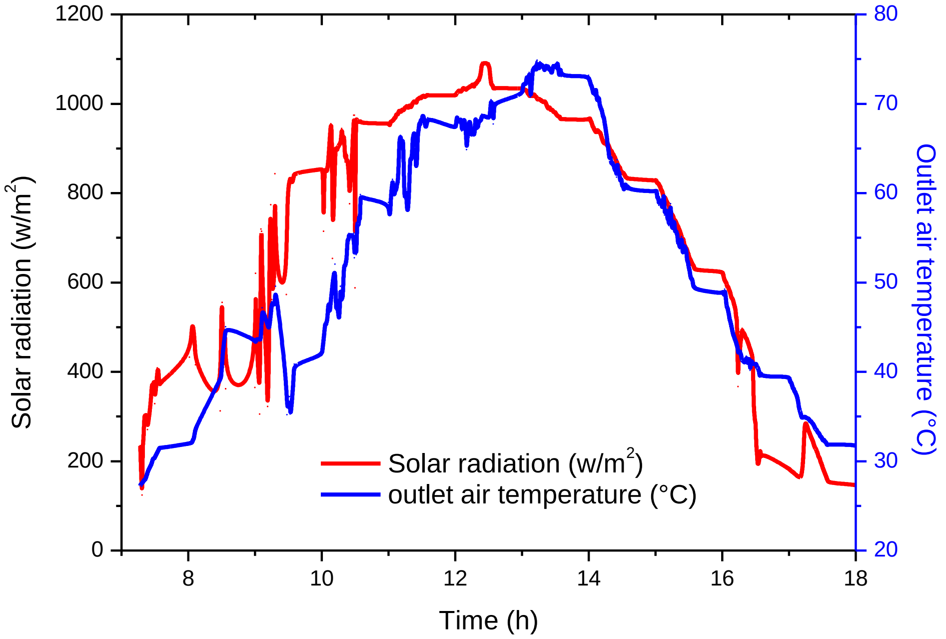

Fig. 12. Hourly variations of solar radiation and outlet air temperature with local time (17.07.2020)

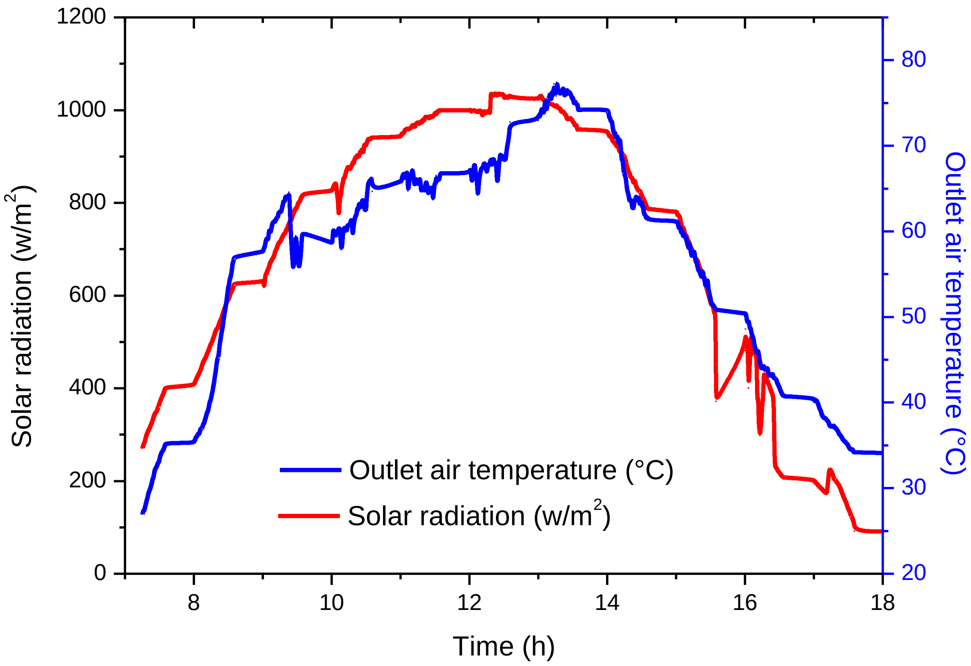

Fig. 13. Hourly variations of solar radiation and outlet air temperature with local time (19.07.2020)

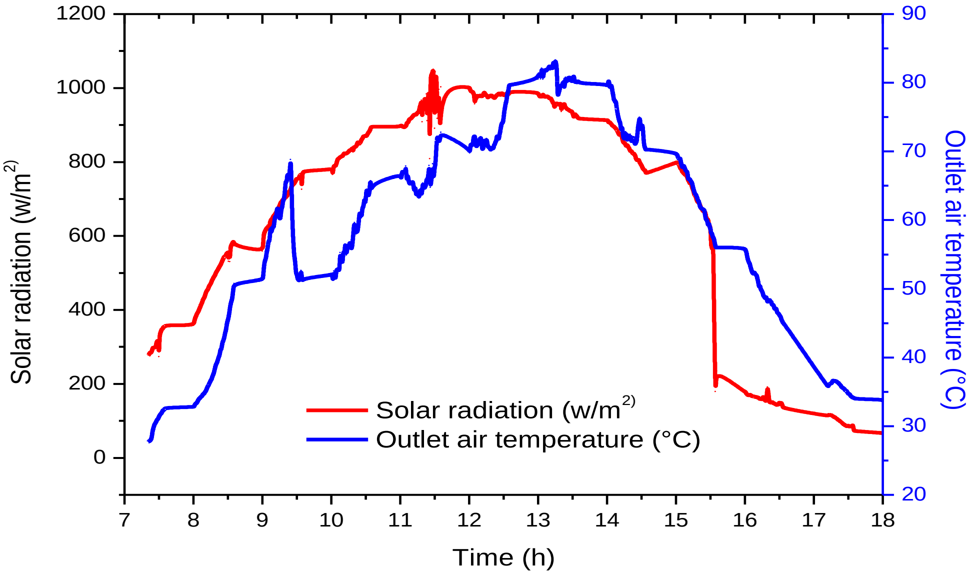

Fig. 14. Hourly variations of solar radiation and outlet water temperature with local time (01.09.2020)

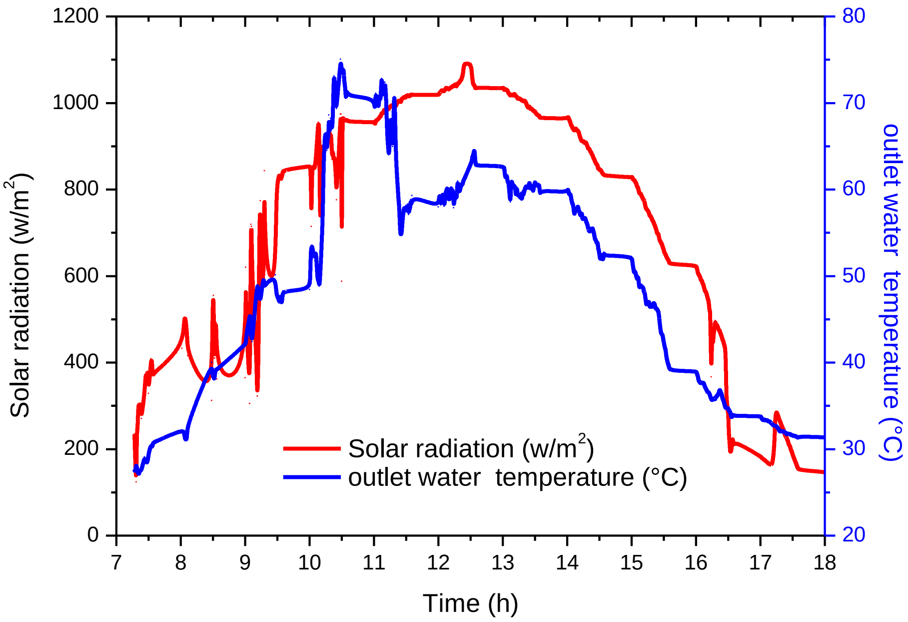

Fig. 15. Hourly variations of solar radiation and outlet water temperature with local time (17.07.2020)

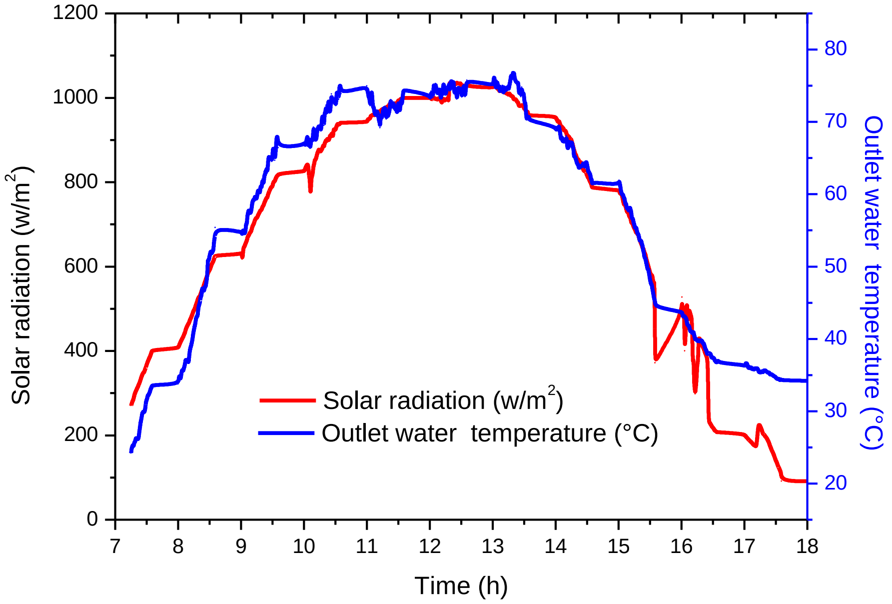

Fig. 16. Hourly variations of solar radiation and outlet water temperature with local time (19.07.2020)

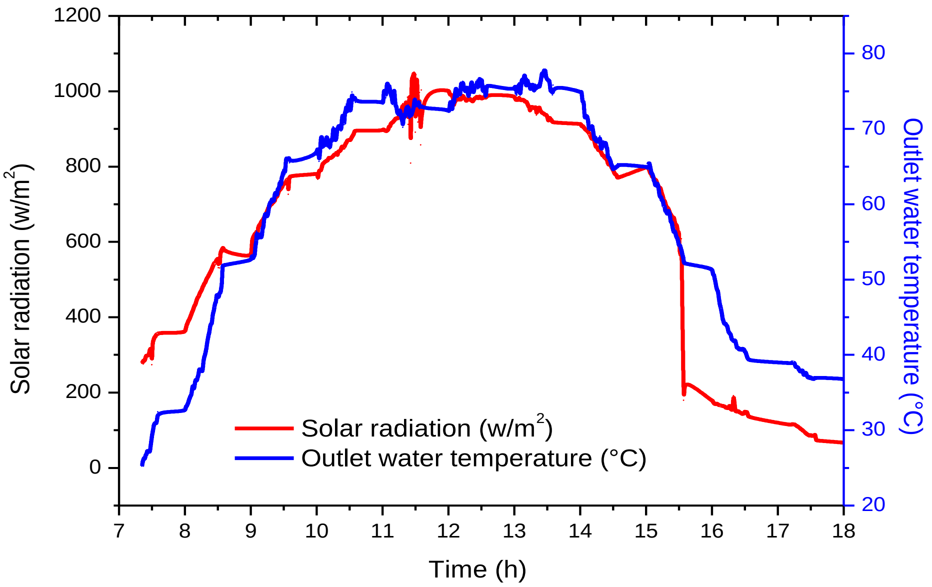

Fig. 17. Hourly variations of solar radiation and outlet water temperature with local time (01.09.2020)

Hourly variations of solar radiation and air temperature at the inlet and in the humidifier with local time shown in Figure 18. The inlet air temperature was the maximum at noon and was about 79 °C. At the indicated climatic conditions as the inlet air temperature increases starting from morning till noon the temperature in the humidifier decreases due to sensible heating of the moist air by air solar collector. It is clear that the fact of heating, air by air solar collector device diminishes its temperature in the humidifier which in its turn leads to increasing the capacity of air to load water vapour by subsequent humidification of air in the humidifier; this can be also confirmed using the psychometric chart of moist air.

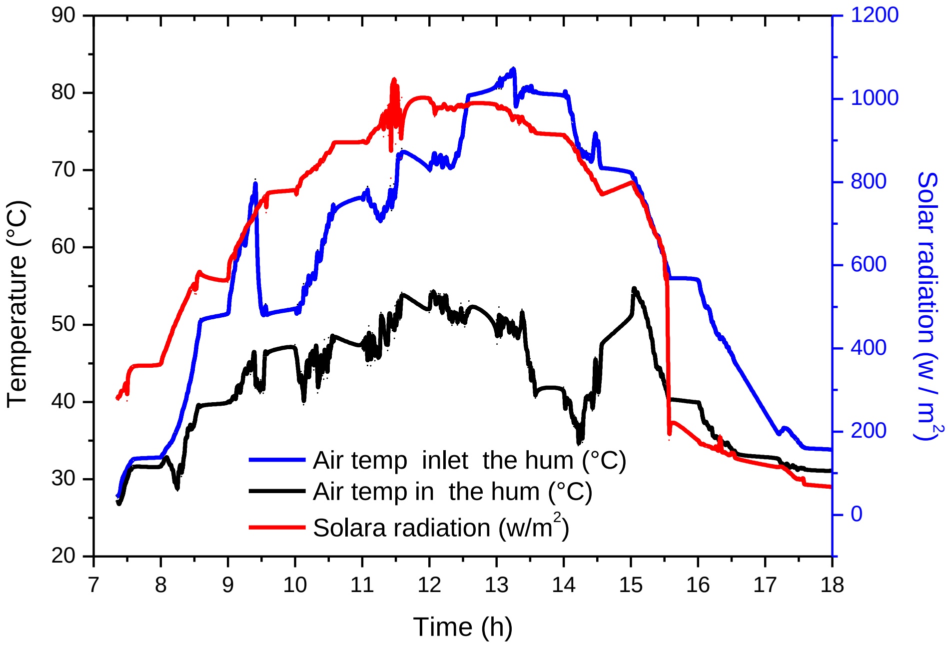

Fig. 18. Hourly variations of solar radiation and air temperature at the inlet and in the humidifier with local time

4. Conclusion

In this work, a modified solar still coupled to a condenser, solar air and water collector and packed bed stepped with humidification- dehumidification system was designed, fabricated and experimentally tested during daytime for each days (summer time) at the city of Sfax, Tunisia climatic conditions. An experimental investigation for single – basin solar still method for water distillation was carried out.

The various temperatures like outside glass cover, solar basin water, water and air temperature initial saline water temperature, air temperature, and ambient temperature of the stills are recorded by using thermocouples and the data is plotted. Thermocouples were located in different places of the solar still and the water and air solar collectors. The solar intensity shows similar variation during the days of the analysis. The periodic variation of the solar intensity for the days of analysis is also plotted. Their average value shows a similar variation in these days. From the results obtained, the following conclusions can be detected

- The water-basin temperature and water-vapor temperature increases fastly corresponding to low increases in ambient temperature.
- The humidification-dehumidification processes increase the hourly productivity of the conventional solar still (CSS) by about 55%.
- The ambient temperature represents the main parameter that affects affected on the distilled water production rate especially at first working hours when it’s still not reaches at maximum value.

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