An Experimental Study of a Solar Still: Application on the sea water desalination of Fouka

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Abstract

Today, seawater and brackish water desalination is a subject of concern of many researchers all over the world. The recourse to the desalination by distillation using solar energy represents an appreciable element of the water resource and constitutes a realizable, simple, profitable, operational solution technically.

The present study, which is essentially experimental, is interested in the effect of the internal parameters on a double slope plane solar still. In this work, the solar still was conceived and realized by our team of research. The experiments were carried out at different conditions. The variation of the different operating parameters of the solar still has been studied. It is found that the distillate production rate increases when the difference between the temperature of water and glass decreases. Distillated water was also influenced by the presence of wind and the climatic changes which decrease the amount of diffuse solar energy received by the brackish water. The average yield of distilled water was 4 L/m²/day.

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Keywords: Desalination, distillation, solar energy, solar still, Sea water, efficiency, electrical conductivity, pH.

1. Introduction

Many developing countries show an increasing interest to the sea water and brackish water desalination by solar distillation. Solar energy is available, free cost and non-extinguishing in nature. In the last few years, many researchers were interested in the sea water and brackish water desalination using solar energy. This thermal process is an efficient solution to pure water scarcity in the world. In fact, there are many types of solar stills, some of them have been developed and commercialized [1, 2, 3]. Till today, many experimental and theoretical studies are undertaken in order to modify the solar still using different configurations and improve its yield [4, 5, 6]. The study of many researchers undertaken in this context, indicate that the yield of the solar still depends on the different external and internal operating parameters and that the produced water quantity varies according to the type of the solar still.

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| Symbol   | Description                                                                 |
|----------|-----------------------------------------------------------------------------|
| $Q_{wg}^c$ | Amount of energy flux transferred by convection from water to glass (W)     |
| $Q_{wg}^r$ | Amount of energy flux transferred by radiation from water to glass (W)      |
| $Q_{wg}^{ev}$ | Amount of energy flux transferred by evaporation from water to glass (W)    |
| $Q_{ga}^c$ | Amount of energy flux transferred by convection from glass to ambient (W)  |
| $Q_{ga}^r$ | Amount of energy flux transferred by radiation from glass to ambient (W)    |
| $Q_{bw}$  | Amount of energy flux transferred from bottom to water (W)                  |
| $Q_{bw}$  | Amount of energy flux transferred by conduction from insulator to ambient (W)|
| $Q_{is-a}^r$ | Amount of energy flux transferred by radiation from insulator to ambient (W) |
| $Q_{is-a}^c$ | Amount of energy flux transferred by convection from insulator to ambient (W) |
| $Q_{cd}$  | Amount of energy flux transferred by conduction from vat to insulator (W)   |
| $Q_{b-is}$ | Amount of energy flux transferred from bottom to insulator (W)              |
| $\eta_g$  | Global efficiency of solar still (%)                                       |
| $I_g$     | Global solar radiation (W m$^{-2}$)                                         |
| $T$       | Temperature (°C)                                                            |
| $\rho$    | Density of water (kg/m$^3$)                                                 |
| $\sigma_e$ | Electrical conductivity (µS/cm)                                             |
| $T_W$     | Water temperature (°C)                                                     |
| $T_{ig}$  | Inner glass temperature (°C)                                                |
| $T_{og}$  | Outer glass temperature (°C)                                                |
| $T_b$     | Vat temperature (°C)                                                       |
| $T_v$     | Vapor temperature (°C)                                                     |
| $T_a$     | Ambient temperature (°C)                                                   |
| $T_{is}$  | Insulator temperature (°C)                                                 |
| $U_L$     | Factor of the global losses                                                 |
| $\alpha_l$ | Absorption coefficient                                                     |
| $L_v$     | Latent heat of evaporation of water (J/kg)                                 |
| $m$       | Rate of the distillate (kg/s)                                               |
| $A_c$     | Area of glass (m$^2$)                                                      |
1. Introduction

Many developing countries show an increasing interest to the sea water and brackish water desalination by solar distillation. Solar energy is available, free cost and non-extinguishing in nature. In the last few years, many researchers were interested in the sea water and brackish water desalination using solar energy. This thermal process is an efficient solution to pure water scarcity in the world. In fact, there are many types of solar stills, some of them have been developed and commercialized [1, 2, 3]. Till today, many experimental and theoretical studies are undertaken in order to modify the solar still using different configurations and improve its yield [4, 5, 6]. The study of many researchers undertaken in this context, indicate that the yield of the solar still depends on the different external and internal operating parameters and that the produced water quantity varies according to the type of the solar still.

In order to improve the productivity of a solar still of hot-box type, L. Cherrared [7] carried out a systematic comparison between a simple solar and solar water-heater still. According to the obtained results, one can conclude that water temperature has an impact on the daily production of the still and its efficiency. Bilal A. Akash et al [8] have studied experimentally the efficiency of a solar still from different inclination angles of the cover 15°, 25°, 35°, 45° et 55°. They noted that the maximum water production is obtained with an inclination angle of 35°. The experimental results obtained, indicate that the water salinity affects the production of the distillate, even at a low concentration. H. Al-Hinai et al [9] used a mathematical model to forecast the productivity of a simple solar still subjected to various climatic parameters and also to the operational and conception parameters of the region of Oman. They noted that the optimum design conditions of the solar still gives an average annual solar yield of 4.15 kg/m² per day. Other studies related to stills equipped with internal and external reflectors were made by Hiroshi Tanaka [10] N. Abdul Jabbar Khalifa et A. Hussein Ibrahim [11] Hiroshi Tanaka et Yasuho Nakatake [12][13]. A theoretical and experimental study was presented by V. Velmuruga et al [14] with some modifications on the still (fin, sponge, and wick) in order to examine the effect of these materials on the productivity of the system. They noted that the experimental analysis is in conformity with the theoretical results. The maximum deviation is of 10% and the productivity improved from 1, 88 to 2, 8 kg/m².

The aim of this work is to examine the effect of water temperature, the ambient temperature and the climatic conditions in the town of Bou Ismail-Algeria (located 36° 38’ N in latitude and 2° 41’ E longitude) on the operating characteristics of the system. The obtained results allow us to present the evolution of different temperatures, the quantity of distillate versus time and the physico-chemical analysis of the distillate.

2. The operating principle

The operating principle of a solar still used for water desalination involves phase change water–vapor. It permits the separation of the water constituents into salts deposits and distilled water. In fact, the solar flow transmitted through the glass cover achieves the absorber, which in return emits thermal radiations, this fact heats water. Under the influence of heat, the vat’s sea water evaporates successively leaving only water’s molecules, a dissolved salt deposit and all other residues in seawater. The obtained vapor condenses and the distilled water streams on the interior face of the inclined slope glass put in drains which drives it into a stocking tank.

The different heat fluxes intervening in the heat transfers which occur within the still become explicit by many physical phenomena.

The various modes of transfer of the exchanged heat between the brine and the glass are done by convention $Q_{wg}^c$, by radiation $Q_{wg}^r$ and by evaporation $Q_{wg}^{ev}$. The still is a system which exchanges the heat with the outside through the glass $Q_{ga}^c$ by convention and bottom and side insulating walls are done by conduction $Q_{is-a}^{cd}$ and radiation $Q_{is-a}^r$. In what follows we determine the heat transfer principle inside and outside the still fig. 1.

The absorber: the water layer receives both by conduction and convection a heat flux $Q_{bw}$ from the absorber and transmits by conduction a flux $Q_{b-is}^{cd}$ to the insulator.
The brine: the brine yields by radiation the flux $Q_{wg}^r$ and by natural convection the flux $Q_{wg}^c$, by evaporation during the change phase a flux $Q_{wg}^{ev}$, on the condensation surface (the interior glass of the still).

The Glass: from the inner side, the glass receives the flux by convection $Q_{wg}^c$, by radiation $Q_{wg}^r$ and by evaporation $Q_{wg}^{ev}$. Consequently, from the inner side, the glass diffuses to the ambient air the equivalent sum of two flows $Q_{ga}^c$ and $Q_{ga}^r$.

The insulator: the insulator receives by conduction a flux $Q_{cd}^{cd}$ from the absorber and can yield to the outside $Q_{is-a}^r$ and $Q_{is-a}^c$ respectively by radiation and convection.

3. Experimentation

3.1 Description of the experimental device

The experimental measurements are performed on a solar still of chapel type realized and conceived by our team of research at UDES. The system consists of a water-tight capacity surmounted by a glazing (fig.2). The basin of the still that is made of materials with glass fibers and a resin layer, represents the lower part of the surface 1.39 m$^2$ painted in black in order to capture the maximum solar energy. The absorber is covered with sea water of 3 cm in depth, characterized by a salinity of 37.7 g/L. The side and the lower walls are insulated by a glass woolen layer of 40 mm of thickness and a thermal performance $\lambda=0.042$ w/m °C to minimize the heat loss into the outside. The whole of the device is fixed on a metal support.

Fig. 2. An overview of the experimental device
3.2 Instrumentation

In our experiment, we used the sea water of Fouka which has a density of \( \rho = 1025.9 \) kg/m\(^3\), an electrical conductivity of 56.6 ms/cm and a pH = 8.01 at a temperature \( T = 23.3 \) °C. The various temperatures were measured by thermocouples of K type connected to a data logger of fluke type for the acquisition of the data which were recorded on a memory board programmed for a time interval of 30 minutes. The thermocouples dispositions are presented in fig.3. The measurements of the distilled water characteristics (salinity, electrical conductivity, pH, TDS) were performed using a conductivimeter of Inolab type (Cond level 1). The global solar irradiation on a horizontal plane was measured by means of a pyranometer type CMP11 « Kipp & ZONEN » whose range of sensitivity is included between 7 and 14 \( \mu \)V/W/m\(^2\). The radiation data were recorded in the weather station of UDES. The distillate water was collected every hour and was measured using a graduated test tube.

4. Results and discussion

The systematization of the experimental tests, allowed us to represent the evolution of the various temperatures versus time, the daily quantity of the distillate, the pH variation, the electrical conductivity, the solar irradiation and the global efficiency of the last two days (30/06/2010 and 06/07/2010) which are represented in the form of curves. The day of 30/06/2010 was sunny, windy, with a clear sky and a maximal temperature of \( T_a = 32 \) °C. On the contrary, the day of 06/07/2010 was sunny, a little bit windy from 13 PM with a maximal temperature of \( T_a = 30.6 \) °C this has an impact on the quantity of the distillate. The daily production of distilled water (30/06/2010 and 06/07/2010) was respectively 5 and 5.38 litre/day.

4.1 Temporal evolution of the solar radiation \( I_g \)

The variation of solar radiation received by an inclined glazing surface \( \theta = 23^\circ \) during the experimental tests is shown in Figure 4. The results show that the solar radiation becomes preponderant and more intense between 12 PM and to 13 PM and decrease from 16 PM because the town of Bou-Ismail is located in a littoral circumference which is marked by a long sunstroke time during July and June. The measurements of solar irradiation obtained show a slightly significant deviation between the day of 30/06/2010 and 06/07/2010 from 9 AM to 13 PM, this explains the increase of the daily production 7.6 %. These results indicate that the production of the distilled water depends strongly of the incidental solar energy.
4.2. Evolution of the temporal distillate production

The Fig. 5 represents the daily evolution of the distilled water production versus time. We note that the condensate production increases steadily and the maximum quantity obtained reaches 800 mL at 15 PM and 14 PM, respectively during the days of 30/06/2010 and 06/07/2010. In fact, we concluded that the distillate production is influenced by the presence of wind during the day of 30/06/2010. We observed that the external parameter has decreased the rate of production during the morning, so the production rate remains constant from 13 PM to 14 PM in comparison to the day of 06/07/2010.
4.3. Effect of the temperatures evolution

The Fig. 6 presents the results of the measurements related to the physical internal parameters according to time. The evolution of different temperatures versus time such as: sea water temperature; inner glass temperature \( T_{ig} \); outer glass temperature \( T_{og} \); vat temperature \( T_{b} \); mixture air/ Vapor temperature; ambient temperature \( T_{a} \) and the insulator temperature \( T_{is} \) obtained during the two days of experimentation indicate that the temperatures increase and reach the maximum rate then it diminishes from 15 PM. We can note a strong variation in the temperatures of the sheet of water, the air/ Vapor zone and the external glass; this favours the evaporation and the condensation processes. It is found that the distillate production increases when the difference between water and glass temperatures decreases.

![Fig 6](image)

To carry out the water quality analysis, the value of two parameters: electrical conductivity and pH were measured before and after the distillation process. Therefore, the values of the ionic conductivity and pH are taken by sampling every 1 hour to study the variation of these parameters during the distillation process.

The Fig. 7 and 8 present the results of the measurements of the electrical conductivity and the pH values, respectively.

One can note that the variation of the electrical conductivity reveals a fairly rapid and remarkable diminution from 9 AM to 13 PM, then it remains constant until 16 PM. On the other hand, the pH decreases with time within the \( 5 \leq \text{pH} \leq 6 \) range for day 30/06/2010, see Fig. 8. The drop in pH is due to carbon dioxide \( \text{CO}_2 \) dissolves in water [15, 16].

The results of measurements demonstrate that the level of water pH produced during the above experiments was between the value of 5 and 6, which is similar to the value of pH in drinking water.
4.4. The study of the variation of the global efficiency versus \((T_w - T_a)/I_g\)

The obtained measurements enable us to present experimentally the evolution of the global efficiency versus \((T_w - T_a)/I_g\) as illustrated on the following figure related to the day 06/07/2010. The global efficiency \(\eta_g\) and internal efficiency \(\eta_i\) of the solar still are expressed by the relation:

\[
\eta_g = \frac{Q_u}{Q_{inc}} = \frac{\sum m L_v}{\sum A_c I_g}
\]

\[
\eta_g = \alpha_i \eta_i
\]

\[
Q_u = A_c \alpha_i I_g - U_l A_c \left( T_w - T_a \right)
\]

\(L_v\) is the latent heat of evaporation at the water temperature and \(\dot{m}\) rate of the distillate.
\[ L_v = 4.18 \left[ 883 - 0.668 \left( T_w + 273.15 \right) \right] \]

\[ \eta_g = \alpha_i - U_l \frac{T_w - T_o}{I_g} \]

\[ \eta_g = A + B \cdot X \]

From the theoretical and experimental equations we get: \( U_L = A, \) \( \alpha_i = B. \)

The constants A and B of the (4) equation are respectively the absorption coefficient (Optical performance) of water and the factor of the global losses of the solar still.

The behaviour of the global efficiency follows a linear law, the regression line slope is positive expressing the factor of the total losses by analogy about \( U_L = 2.76 \text{W/m}^2\text{°C}. \) In comparison, the experimental results agree with those found in literature, which are of the order 3 to 4 \( \text{W/m}^2\text{°C}. \) By contrast, the losses factor is relatively low compared to the theoretical value estimated \( U_L = 5.12 \text{W/m}^2\text{°C}. \) Concerning the fictive absorption coefficient \( \alpha_i \) of the water mass is found experimentally 0.16, this optical performance of the still seems very low in comparison to the theoretical value 0.85, this can be explained by the presence of an important mass of salt deposit at the bottom of the vat.

The performed analysis enable us to examine the evolution of the global efficiency versus sea water temperature during the local time interval from 10 AM to 14 PM for the day of 06/07/2010. The evolution of \( \eta_g \) obeys to a linear law of the positive slope. In fact, we recorded a rapid increase of these characteristics. When the sea water temperature increases, we noted that the yield increases in time interval for high temperatures reaching 70 °C to 107 °C (Fig.9 (b)).

5. Conclusion

A double slope solar still was manufactured and tested under the solar radiation. This experimental study permits to examine the influence of some internal and external parameters on the operating system and their temporal evolution. According to this analysis, the sea water desalination process by solar distillation seems to be influenced by the different effects that have an impact on the considered still yield as, the solar energy, the distilled water temperatures, the thickness of the water layer and the salts deposit.
The realised experiments, permitted to note the modifications related to the evolution of the global efficiency such as the global losses factor obtained experimentally $U_L = 2.76 \text{ W/m}^2\text{°C}$. This one agrees with the results reported in the literature, which is of the order 3 to 4 W/m$^2$°C. The wind and the salts deposits decrease relatively the rate of the distilled water production. The incidental solar radiation and the difference in temperature between sea water and the ambiance tend to accelerate the physical phenomenon of the solar distillation between 12PM and 15PM. This qualitative study proves that solar distillation of sea water is a good option for water treatment. The average yield of distilled water obtained by solar desalination was 4 L/m$^2$ /day.

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