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Impact of temperature difference (water-solar collector) on solar-still global efficiency

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Abstract

Different theoretical and experimental studies carried out in the field of solar distillation with green-house effect, have shown that global efficiency of a simple solar still are affected by physical and building parameters, especially by the difference of temperature between the evaporation surface and that of the condensation. Optimising this difference allows us to obtain a solar still with a better efficiency. A mathematical modelling has been carried out aided by some basic and simplified hypotheses, according to overall thermal balances and appropriate heat and mass coefficients, while taking into consideration a stagnant area in the solar still. Resolution of equations, based on method of finite differences, has shown that a better efficiency is obtained at a maximum temperature difference, as well as we can obtain this latter by a low glass thickness, a gradient (angle of inclination) closer to that of the area latitude, in which our solar still is placed, a low thickness of the solution to be distilled and a high wind velocity. Results issued from this study show clearly the importance of a cooled condensation surface and a hotter evaporation surface.

Keywords: Backish-water desalination; Solar distillation; Global efficiency; Evaporation; Condensation; Temperature difference

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1. Introduction

Considering the increasing demand on water all over the world and the water resources depletion, sea-water and/or brackish-water desalination are considered, in fact, as a contemplated principle to realise, in order to obtain soft or drinking water. In Algeria, the problem of water supply is being faced, where saline water is available and desalination represents a solution for water resources increase.

Progress in desalination has been made to the point where industrial units have been set up using energy with a high cost price of a produced water cubic meters. In spite of having a low efficiency, solar distillation proved to be a process of soft-water production, economically

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viable, particularly in desert areas, which have an important solar deposit and where rainfall is rare or mostly absent. However, in the case of the south of Algeria, an important groundwater resource, mostly brackish, is available and where solar distillation can be an adequate solution to face the increasing demand on soft water.

The aim of our work is to study the energetic global efficiency of a solar still with a greenhouse effect, which is dependent on the temperature difference between the brine and the inner side of the glass, on the climate and geometric parameters and on those related to the brine. A theoretical study has been carried out in order to set up equations governing the performance system as well as parameters influencing solar-still efficiency.

By knowing equations governing the inner and the outer heat transfer and through experimental models, we can, by mathematical simulation, set up an adequate solar still and elaborate a mathematical model, being able to meet distilled-water demand and where efficiency can reach acceptable values.

2. Literature review

It seems that Egyptians who discovered first green-house effect. Use of solar energy began in the third century before J. C, by Archimedes and 100 years after J. C, by Heron of Alexandria, in 1615 by Salomon de Gauss, in 1774 by Joseph Priestley and in 1878 a solar still of 5000 m^2 has been set up in the desert of Atacama (Chile), in order to supply in water a mine of sodium nitrate. After 1878, works on solar energy has slow down because of fossil energy availability in a lower cost. Solar energy has been reused from 1902 to 1908, by Schuman who built up solar machines with much horse power to pump water.

In 1913, Boys set up, near Cairo (Egypt), a big machine of 50 horse power with lengthy parabolic cylinders which concentrates solar radiations upon a central pipe with a concentration factor of 4.5, in order to pump water from the Nile River for irrigation purpose.

Solar energy still being used till 1938, from which there was no other progress in solar-energy field, because of its lack of competitiveness compared to energy issued from fossil fuels. From 1950, use of solar energy, began to develop slowly [1]. Among solar energy uses, we can quote heating and air conditioning for respectively building, solar swimming-pools, salt production through salted-water evaporation, drying products issued from agriculture and animals, solar cookers and pumps, food preservation, photovoltaic conversion, solar furnace, electricity production, indirect solar-energy conversion, wind energy, hot-water production and for domestic and industrial use and distilled water [2].

3. Main characteristics of saline water

Water resources the world is mostly saline, of which an excessive salt content renders their use inappropriate for human activities, and where salt elimination is required. Sea water and brackish water can then be distilled.

Sea-water composition is variable; it contains about fifty simple substances, where chlorine represents 55% from the total weight of the dissolved salts. However, sea-water salinity is closer to 35 g/l, but it changes from one sea to another.

Brackish water is defined as saline water not drinkable, where its salinity is lower than that from sea water; this salinity is usually contained between 1 and 33 g/l. Brackish water can be identified by its degree of salinity: waters called slightly brackish have a salinity between 1 and 3 g/l. Moderately brackish waters have a salinity between 3 and 10 g/l. High brackish waters have a salinity beyond 10 g/l. The first two categories are the most widespread, usually found in North Africa, in Middle Eastern countries and in some areas of USA. Chemical composition of this type of water changes also, for the same area, from one season to another, and is dependent on many parameters such as physical structures of the rocks through which water is flowing, water flow-velocity inside the rocks, the contact time, the already dissolved substance and the evaporation phenomena.

4. Desalination techniques

We can operate desalination for sea water from which salinity is closer to 35 g/l, or for brackish water having salinity between 1 and 10 g/l. However, there is a thermodynamic problem relied to the source of water to be desalinated, where efficiency is different. We therefore notice that brackish water, for its salinity, requires less energy for its desalination than that required by sea water, which means that efficiency is different (Table 1). For this reason, there are processes of desalination being used which are classified into two groups:

- Distillation process (simple-effect distillation, multiple-effect distillation, distillation by vapour compression and distillation “flash”) [3].
- Membrane process, which is a simple technique used at ambient temperatures and consuming only electric or mechanic energy (electro-dialyse process and reverse osmoses) [4].

Table 1
Comparison of energy quantities used for brackish-water and sea-water desalination

Soft water (%)	Energy/m^3 (kW) initial water:sea water	Energy/m^3 (kW) initial water: brackish water
10	0.8	0.032
50	1.10	0.174
90	2.20	0.290

5. Solar distillation

Solar distillation is used to supply small communities with soft water, where drinking water is hardly existent. Solar distillation has been used since many centuries. Mouchot has reported that the Arab alchemists are the first to have set up, in 1551, apparatus for water distillation [5]. The French chemist Lavaoisier has used, in 1862, wide glass lenses, to concentrate solar rays to distillate water being inside the flasks [5].

The first conventional solar still is appeared in 1872 near Las Salinas (north of Chile). The model has been made up by Carlos Wilson, a Swedish engineer, with a glazed surface spread over 5000 m^2; it worked till only 1910, because of a major problem relied to the rapid accumulation of salts in the basin, requiring then a regular cleaning of the still [6].

In 1920, Kaush has used a metallic reflector to concentrate solar rays [6]. Pasteur has used, in 1928, many concentrators to focus solar rays in order to heat water through a boiler. At the beginning of the thirties, Trifinov has proposed a cylindrical still [7]. Abbot has, in 1938, used cylindrical and parabolic reflectors, to concentrate solar rays and where the overall is conveyed in tubes filled with water [7]. Maria Telks has, in 1945, discovered a new type of solar still called “spherical still”, used by the American marines: about 200,000 of this model have been used during the world war. As there was a drought, just after the war, they used solar distillation as an alternate solution to the problem. Cooper has, in 1969, proposed a simulation to analyse efficiency of green-house solar still [8].

Since the 1970s, many other types of solar stills have been elaborated and studied, from which we can quote: multiple-effect solar still, steeped plate or steeped solar still, wick solar still or multiple-wick solar still and the combined solar still–green house [9].

Many countries have then approached solar still, like Algeria (1963) [10], Australia (1963 and 1967) [11], Chile (1969 and 1970) [12], Greece (1964–1973) [11], India (1957 and 1966) [12,13], Tunisia (1960) [14] and USA (1952) [15].

6. Typical solar stills

We can distinguish two types of solar stills with green-house effect: static stills (still with green-house effect, solar still with cascade, sweeping spherical still, steeped still with a black and porous material and soil–water still) and streaming solar stills.

7. Theoretical study of a solar still

The aim of the study is to analyse the behaviour of different solar-still components as well as parameters having an effect on the solar-still performance: the cover (through its nature, its transmittance, its wetness and its inclination degree), the black plane, the space between the brine and the cover, the brine thickness, the brine temperature, the wind velocity, the ambient temperature and the salt concentration. The aim of this work is also to study the main solar-still characteristics, through its global and internal efficiency.

In our case, we have selected a static solar still with a simple green-house effect, for its quality like its simple design, its high daily output and because it does not require a stocking system and it is economic [16].

We are interested also to models taking into account global thermal balance by bringing in a stagnant zone called “buffer zone”, inside the solar still and where temperature and surface pressure of vapour are constant as described also in Baum model [17]. A mathematical model has been set up, expressing the performance of a static solar still with a regular geometry [16]. This device distils a charge of pure water, maintained constant and subject to a constant global-solar flow (Fig. 1).

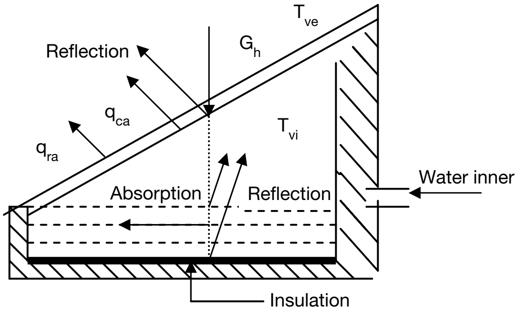


Fig. 1. Static solar still with a simple effect.

8. Basic hypotheses of simplification

In order to avoid complicating the study of this type of solar still, we allowed the following hypotheses:

- Temperatures of respectively the inner and the outer sides of the glass, of the brine, of the absorber and inside the insulator are supposed uniform;
- Water condensation on the cover is homogeneous and continuous;
- Lateral sides are at constant pressure (adiabatic);
- Heat loss in the basin comes from the basis;
- Brine inside the basin is static;
- The vault is considered as a black body;
- Physical properties of materials are considered constant;
- Brine concentration does not intervene in the mass and heat transfer, from and to the brine.

Finally, an analogy between thermal and electric dimensions has been carried out.

9. Thermal balance

The thermal balance is carried out regarding to the following law:

$$\frac{M_i \cdot cp_i}{S_i} \cdot \frac{dT_i}{dt} \qquad (1)$$

The balance is carried throughout: the cover (inner and outer sides), the brine, the black surface and the insulation (inner and outer sides).

10. Mathematical resolution

The aim, here, is to study the model behaviour, which is relied to spatial and temporal divisions of some spatial sections having a length “Δx”, corresponding to the flow direction and to periods “Δt”, in the interval time “$t + \Delta t$”, we describe then all the system from the first to the last section. Resolution of the equation system, expressing thermal and mass balances, gives temperature distribution for each section. The calculation is developed as follows:

- At the initial time, all the elements are supposed at ambient temperature excepting the brine temperature.
- At each step time, and for each section, we resolve the equation system by fixing parameters governing the system work, represented essentially by the temperature.

Computation procedure is carried out according to the following steps:

- Computation of thermal-exchange coefficients between the different elements, represented by their temperatures at the instant “t”;
- Re-computing temperatures from thermal-exchange coefficient being already computed;
- Re-computing thermal-exchange temperature from the new temperatures.

The two last steps are then repeated till we reach accuracy between two successive iterations, then, we carry out the same model (algorithm) for the interval “$t + \Delta t$”, “$t + 2\Delta t$”, etc. till a complete use of time “t”.

In our case, the solar still has been divided, in the space term, into two parts from which the width is 50 cm and a step time is of one hour, which usually suits well the distillation system.

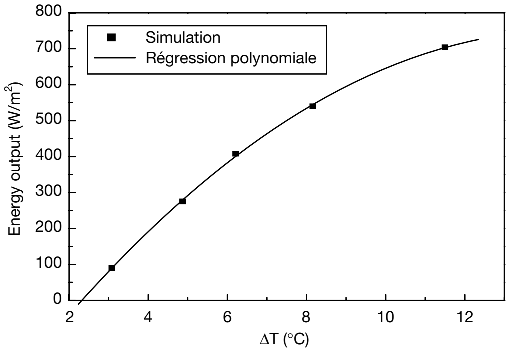
11. Interpretation and discussion of the results

The resolution of equations has allowed us to obtain results, where computation has been carried out for each component of the still at an initial time “t” and at an initial temperature “T_e” with a time step equals to 1 h, and taking into account geographical coordinates such as the longitude and the time lag of the considered area (Ouargla, south of Algeria) and where meteorological and design parameters have been selected for the day of July 15th.

In addition to remarks that we can make about the different parameters affecting the solar still, we can limit our discussion about the impact of the temperature difference “Δt” on the energy output (Fig. 2) and on the efficiency (Fig. 3), in one hand and about the effect of wind velocity, the inclination angle “β” and glass thickness on the same temperature (Figs. 4–6) in another hand.

Throughout the different results issued from the simulation, we notice that the solar-still energy output and the power absorbed by the glass and the brine reach their maximum value between 11.00 a.m. and 3.00 p.m.

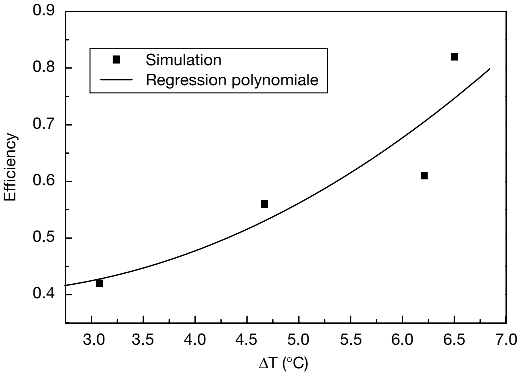
We notice also that the temperature is increasing at the inner side of the glass “T_{vi}”, which is due to different heat flows (by convection, radiation and evaporation), going up to the glass (Fig. 2).



$e_v = 0.002$ m, $\beta = 30°$, $V = 2.5$ m/h, $e_s = 0.02$ m

q_{evap}: $Y = 311.45 + 145.59 \times X - 4.98 \times X^2$; $R^2 = 0.999$; $P = 4.37 \times 10^{-4}$

Fig. 2. Variation of the evaporated energy output with ΔT.



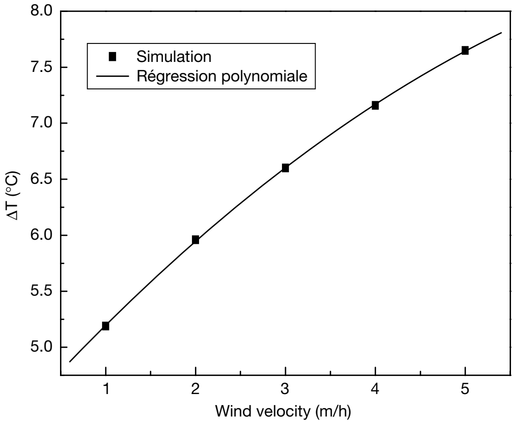
$e_v = 0.002$ m, $\beta = 30°$, $V = 2.5$ m/h, $e_s = 0.02$ m

Efficiency: $Y = 0.455 - 0.057 \times X + 0.0157 \times X^2$; $R^2 = 0.81$; $P = 0.043$

Fig. 3. Variation of the global efficiency with ΔT.

As we can also notice that the temperature change is more and more slow, which may due to the important heat loss due essentially to convection and infrared radiation of the glass to external environment.

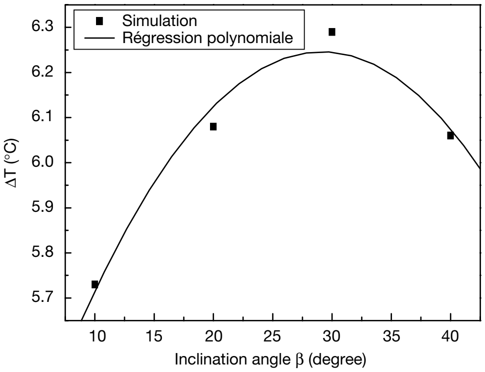
A better global efficiency has taken place at 2.00 p.m., which can be explained by the existing, at this time, of a better sunshine intensity as well as a better temperature difference between the brine and the glass, yielding an important quantity of evaporated energy (Fig. 3).



$e_v = 0.002$ m, $\beta = 30°$, $e_s = 0.02$ m, heure locale = 13 h

ΔT: $Y = 4.35 + 0.886 \times X + 0.0226 \times X^2$; $R^2 = 0.999$; $P = 1.01 \times 10^{-4}$

Fig. 4. Variation of the temperature difference (ΔT) with wind velocity.



$e_v = 0.002$, $V = 2.5$ m/h, $e_s = 0.01$ m

ΔT: $Y = 5.015 + 0.0845 \times X - 0.00145 \times X^2$; $R^2 = 0.971$; $P = 0.016$

Fig. 5. Variation of Δt with the inclination angle β.

The increasing in wind velocity, leads to an increasing production in distilled water, as well as to a better cooling of the inner and the outer glass sides, followed by an important temperature difference between the brine and the inner side of the glass (Fig. 4), where this difference is of a great interest, as it represents the cooler agent of the glass and where the external heat losses by convection can reach their maximum, as the coefficient of external heat exchange is dependent on the wind velocity according to the relation:

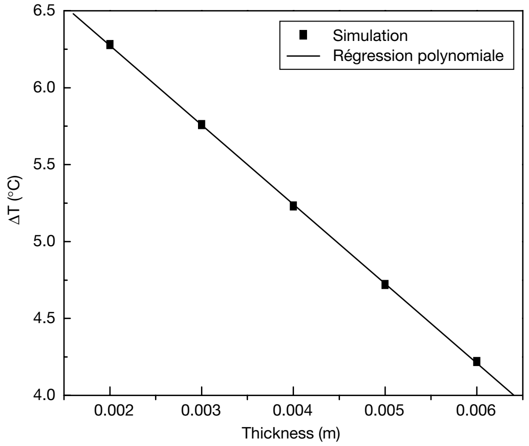
$$h = 5.7 + 3.8 \cdot V \tag{2}$$

We notice also that "ΔT" is reaching its maximum for the same inclination (Fig. 5), yielding to a better efficiency (Fig. 3). However, the power absorbed by the brine decreases, as it receives less energy and from which a part of this energy is absorbed by the thick glass, reducing then the temperature difference between the brine and that from the inner side of the glass (Fig. 6).

12. Conclusions and recommendations

Elaborating this work has allowed us to set up a model, being able to simulate the performance of a solar still with a simple green-house effect.

After setting up equations describing different phenomena governing the solar-still performance,



$\beta = 30°$, $V = 2.5$ m/h, $e_s = 0.02$ m, local hour = 13.00

$\underline{\Delta T}$: $Y = 7.306 - 516 \times X$; $R^2 = 0.999$; $P<0.0001$

Fig. 6. Variation of the temperature difference (ΔT). with glass thickness.

we have set up a programme in order to define the optimum conditions to realise a better efficiency of the system. Resolution of the equations has been carried out through finite-elements method. Using this programme, we have first computed the instantaneous temperature through the different components of the solar still, the temperature difference between the brine and the inner side of the glass, and then the global efficiency and the daily production issued both from the model.

We have also studied the effect of the meteorological and geometrical parameters on the temperature difference between the brine and the inner side of the glass such as: the glass inclination in relation with the horizontal position, the wind velocity, the initial brine thickness and the glass thickness as well. We studied also the effect of this difference on the global efficiency and on the distilled-water production, where the obtained results allow us to observe that:

- The increasing of temperature difference between the brine and the glass leads to a better efficiency as well as a better production.
- The best inclination is that which is identical to the area latitude where the solar–still system is set up.
- A higher temperature difference is obtained through the increasing of wind velocity, in other words, through the increasing of external-exchange coefficient by convection. Therefore, we can say that design of such a solar still needs to optimise parameters relied to its form and to its performance. A better optimisation can also be obtained by a compromise between respectively the glass inclination, the water thickness, the wind velocity, the type of the absorber as well as that of the insulator.

In our case, a better production has been obtained by using copper as the absorber material having 3 mm in thickness and painted on black dull, and an ordinary glass having 2 mm in thickness and having an inclination angle of 30° and where a soaked glass is preferred. While in the opposite case, we may have a condensation in drops, giving a relatively important reflected-radiation, and finally a wind velocity of 2.5 m/h.

In order to obtain a higher temperature difference, we recommend:

- A preliminary heating of the brine before bringing it into the solar still.
- A cooling of the glass by using a fan working with an electrical energy which is produced by a photovoltaic system.
- A cooling of the outer side of the glass by flowing first the brine through the glass, before bringing it into the solar still.
- And the use of glass having blades at its external side, in order to increase heat losses by convection, leading to cooling the inner side of the glass.

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