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Improving the design, modeling and simulation in dynamic mode of a solar still

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ABSTRACT

Solar distillation greenhouse is one of the applications of solar thermal conversion at low temperatures. The present work is a theoretical study of a solar still with enhanced single-acting. In the present work, we propose to establish a mathematical model reflecting the operation of a solar still. The proposed research is to improve the production of a solar still by making changes in the design of the conventional solar still by adding a trim-level distiller which plays the role of a humidifier, a pulverizer, and a condenser to study the effect of internal and external parameters of the operation of a solar still. For this purpose, a system of equations governing the operation of the distiller and the different heat exchange coefficients is established. A global mathematical model based on heat and mass transfers is developed in dynamic state regime to investigate both the effect of different operating modes and the variation of functioning parameters and weather conditions on the freshwater production. The results obtained show the influence of external and internal parameters on the operating characteristics of the solar still, in particular production and performance. It was found that the maximum values of production rate, water temperature, and glass temperature are varying inversely with heat capacity of basin water and other materials used in the basin. The total production also decreases with the increase of basin heat capacity.

Keywords: Solar energy; Solar still; Packed bed; Modeling and simulation; Distilled water; Condenser; Water collector

1. Introduction

Solar stills are an important alternative that can be established, mainly for remote areas, because of the benefits they have been recognized for, since no skilled operators are needed. Besides, simple construction solutions can be applied. However, these distillers cannot compete with other types of distillers, in particular for the production of large quantities of water. They seem to be useful in providing small communities with fresh water with low efficiency for the water heating process. Evaporation and condensation occur in a single closed container. In fact, the brackish water acts as a heat absorber and evaporator, while the glass lid acts as a capacitor.

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According to literature review, there are many investigators who have developed and studied various configurations of solar still systems. The following is a summary of some of the literature studies.

Velmurugana et al. [1] found that the various factors affecting the productivity of solar stills are solar intensity, wind velocity, ambient temperature, water–glass temperature difference, free surface area of water, absorber plate area, temperature of the inlet water, glass angle, and depth of water. The solar intensity, wind velocity, and ambient temperature cannot be controlled as they are metrological parameters, whereas the remaining parameters can be varied to enhance the productivity of the solar stills.

The depth of water in the solar still inversely affects the productivity of the solar still. Maintaining the minimum depth in the solar still is very difficult. For maintaining minimum depth, wicks [2,3], plastic water purifier [4], and stepped solar still [5–9] were used. Investigations indicated that a reduction of the brine depth in the still improves the productivity, mainly due to the higher basin temperature. Velmurugan et al. [5] used a stepped still and a settling tank to desalinate the textile effluent. A maximum increase in productivity of 98% is reported in stepped solar still when fin, sponge, and pebbles are used in this basin.

In addition, Velmurugan et al. [6,7] studied the augmentation of saline streams in solar stills integrated with a mini solar pond. When an industrial effluent was used as feed for fin-type single-basin solar still and stepped solar still, a maximum productivity of 100% was obtained when the fin-type solar still was integrated with pebbles and sponges. When a mini solar pond, a stepped solar still, and a single-basin solar still are put in series, a maximum productivity of 80% is obtained, when fins and sponges are used in both solar stills. When a mini solar pond, a stepped solar still, and a wick-type solar still are connected in series, it is found that a maximum productivity of 78% occur, when fins and sponges are used in the stepped solar still.

A weir-type cascade solar still, integrated with latent heat thermal energy storage system, was designed with the view of enhancing productivity [8]. A heat storage system with 18 kg mass (2 cm thickness) of paraffin wax beneath the absorber plate was used to keep the operating temperature of the still high enough to produce distillated water during the lack of sunshine, particularly at night.

The effect of varying both the depth and width of trays on the performance of the stepped still was studied theoretically and experimentally by Kabeel et al. [9]. The results show that, maximum productivity of stepped still is achieved at a tray depth $H = 5$ mm and tray width $W = 120$ mm, which is about 57.3% higher than that of the conventional still.

For further augmentation of the yield, a wick on the vertical sides was added to the stepped still. It is found that the augmentation of the daily productivity of the stepped still by using a wick on the vertical sides is approximately from 3 to 5%. El-Zahaby et al. [10] investigated experimentally a new design of a stepped solar desalination system with a flashing chamber. The main objective of the investigation was to study the performance of step-wise water basin coupled with a spray water system by augmenting desalination productivity through the use of two air heaters.

Reflectors are used to maximize the yield of the solar still. Monowe et al. [11] designed a portable thermal–electrical solar still with an external reflecting booster and an outside condenser. Results show that the efficiency of such a still could be up to 77% if the preheated saline water is used for domestic purposes, and it could be up to 85% if preheated saline water is used to operate the still during night-times and to recharge the still by the next batch of preheated water.

Tanaka [12] constructed a basin-type solar still with internal and external reflectors. The daily productivity of a basin-type still was increased by about 70–100% with a very simple modification using internal and external reflectors. Also, Tanaka [13,14] analyzed theoretically a basin-type solar still and a tilted wick solar still with a flat plate external bottom reflector.

Salah Abdallah et al. [15] improved the single-slope solar still performance through increasing the production rate of distilled water. Design modifications were introduced to the conventional solar still, involving the installation of reflecting mirrors on all interior sides, replacing the flat basin by a step-wise basin and by coupling the conventional solar still with a sun-tracking system.

The inclusion of internal mirrors improved the thermal performance system up to 30%. Kostic and Pavlovic [16] analyzed a solar collector with top and bottom reflectors and calculated the optimum yearly tilt angle for both reflectors for a fixed collector tilt angle of 45° (43°N Latitude). Nikolic and Lukic [17] carried out a mathematical model for determining the optimum reflector position of the double exposure flat plate solar collector in the condition where the lower absorber surface is fully irradiated. Additionally, the model was simulated to determine the optimal reflector positions for the optimum collector yearly position.

Ben Bacha and Zhani [18] 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.

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.
- Material energy storage in the basin distiller to extend the operation of the distiller at night through the storage of excess energy.
- 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 separate condenser for the solar distiller where condensation is produced at a temperature below that of the glass cover.

The objective of this work is to:

- Establish the global model of the unit by modeling each component of the unit independently. Therefore, models, simple solar distillers, and solar water humidifiers (packed bed), respectively, will be presented in this work.
- Follow the dynamic behavior of the output parameters of these two components of the unit (solar water and solar still) based on its inputs and external disturbances.

2. System description

Fig. 1 shows a three-dimensional simplified schematization of the water desalination unit by solar energy. The desalination process of the installation proposed uses the humidification and dehumidification principle. Energy collection is performed by means of the solar collector and of the solar distiller. 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, water will be heated in a solar water plan. Water will be sprayed in the form of small particles by means of atomizing nozzles with high pressure or a compressed air nozzle or a piezoelectric transducer generating ultrasound. The water vaporizes in the distiller and is injected into the condensation stage to ensure the dehumidification of the vapor obtained. By cons, in packed columns, the liquid is sprayed on the packed bed between 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 produced will be collected in a tray placed below the condensation chamber. 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.

3. Dynamic modeling of the various stages of the unit

The modeling of a thermal system is a classical approach which is very developed in the literature; however, this one differs significantly depending on the purpose assigned to the modeling phase. In fact, J, Mignot [19] found that two major axes can be identified:

- First of all, modeling the system for his detailed study and a structural optimization.
- On the other hand, modeling in order to control a process.

We have developed a steady-state mathematical model based on heat and mass transfers in each component of the unit.

The water desalination unit by solar energy using the principle of humidification/dehumidification can be considered as an important class of thermal processes because of the presence of phenomena heating, evaporation, and condensation. It is characterized by the fact that these quantities are different depending on the space and time. So, the dynamic behavior of this type of process is generally described by distributed parameter systems represented by systems of PDEs.

3.1. Water solar collector modeling

The flat plate water solar collector has an absorber with parallel and narrow channels. In this case, the fluid circulates in a forced convection and in one direction. The principal assumptions used to obtain the mathematical model under steady-state regime are:

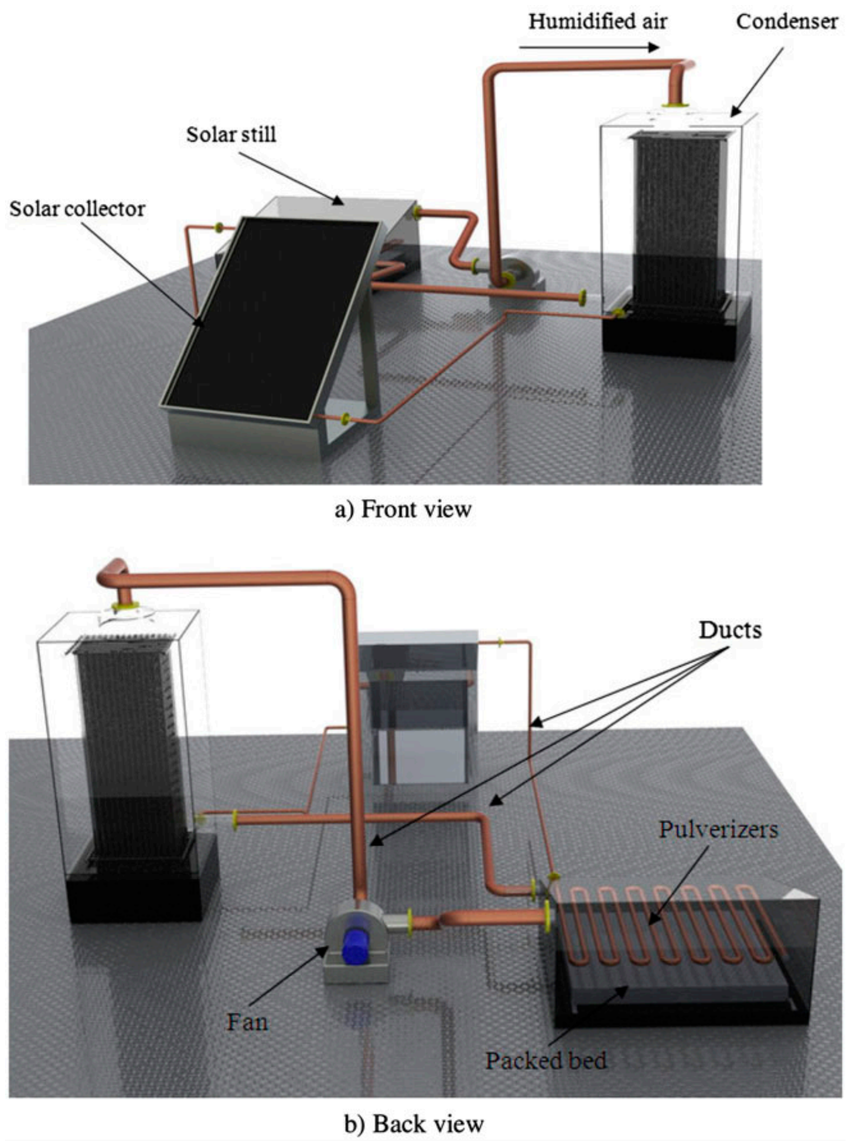

Fig. 1. Design of the distillation unit in three-dimensional: (a) front view and (b) back view.

To establish the model for the solar collector, the following assumptions are listed below by Zhani et al. [20].

- The velocity of water is uniform; therefore, the local state of air depends only on one side x.
- The water temperature remains under 100°C point.

The energy balance equation for the system formed by the absorber and the fluid for a slice of the collector with a width of l, a length of dx, and a surface of ds is the next one:

$$\frac{\partial T_w}{\partial t} = \frac{1}{\delta}\left(-m_w \xi \frac{\partial T_w}{\partial x} - T_w + f(t)\right) \quad (1)$$

3.2. Solar still modeling

- At the glass:

[(The amount of energy accumulated by the weight of glass)] = [(the amount of energy received by an element of the glass cover of width L and of length dx and for a time dt) + (the amount of energy transferred by radiation from the water to the glass during dt) + (the amount of energy transferred by convection (evaporation) from the water to the glass during dt) − (amount of energy transferred by radiation and convection to the ambient air during dt)].

Mathematically, this can be expressed as:

$$M_v C_v dT_v = IA_v \mathrm{d}t + h_{rwv}(T_w - T_v)\mathrm{d}t + h_{evp}(T_w - T_v)\mathrm{d}t - h_{rc}(T_v - T_{amb})\mathrm{d}t \quad (2)$$

It can be further simplified as:

$$\frac{dT_v}{\mathrm{d}t} = \frac{1}{M_v C_v}(IA_v + h_{rwv}(T_w - T_v) + h_{evp}(T_w - T_v) - h_{rc}(T_v - T_{amb})) \quad (2')$$

• Heat balance for the basin absorber:

[(The amount of energy accumulated by the absorber basin)] = [(the amount of energy received by an element of absorber of width L and length dx and for a time dt) − (the amount of energy transferred by convection to the water for dt) − (amount of energy lost to the outside during a time dt)].

Mathematically, this can be expressed as:

$$M_b C_b \mathrm{d}T_b = IA_b \mathrm{d}t - h_{cbw}(T_b - T_w)\mathrm{d}t - U_{loss}(T_b - T_{amb})\mathrm{d}t \quad (3)$$

It can be further simplified as:

$$\frac{dT_b}{\mathrm{d}t} = \frac{1}{M_b C_b}(IA_b - h_{cbw}(T_b - T_w) - U_{loss}(T_b - T_{amb})) \quad (3')$$

• Heat balance for the water basin:

[(The amount of energy accumulated by the water basin)] = [(the amount of energy received by a volume element of water for a time dt) − (amount of energy transferred by radiation from the water into the glass during dt) − (amount of energy transferred by convection from the water into the glass during dt) − (amount of energy transferred by the evaporation of water into the glass during dt)].

Mathematically, this can be expressed as:

$$(M_w C_w \mathrm{d}T_w + M_{st} C_{st}) = IA_w \mathrm{d}t + h_{cbw}(T_b - T_w)\mathrm{d}t - h_{rwv}(T_w - T_v)\mathrm{d}t - h_{cwv}(T_w - T_v)\mathrm{d}t - h_{evp}(T_w - T_v)dt \quad (4)$$

It can be further simplified as:

$$\frac{\mathrm{d}T_w}{\mathrm{d}t} = \frac{1}{(M_w C_w + M_{st} C_{st})}(IA_w + h_{cbw}(T_b - T_w) - h_{rwv}(T_w - T_v) - h_{cwv}(T_w - T_v) - h_{evp}(T_w - T_v)) \quad (4')$$

• Heat and mass balance at the packed bed:

To develop a mathematical model that describes accurately the behavior of distiller (at packing), we divide the latter in volume elements of length dx and apply in second place the balances of heat and mass transfer on the volume element we choose.

The formulation of the mathematical model based on heat and mass balances can determine the coupling equations between the water temperature, the air temperature, and the water content of the moist air in the packed bed.

To establish the heat and mass balances of the packing used in the method, the object of this work, or our theoretical approach, is to consider the the following assumptions and simplifications:

- Considering that the flow is in countercurrent.
- The air and water flows through the packed bed are one-dimensional.
- Considering that the specific heat of water is constant during its passage through the packing,
- Humidification is assumed to be adiabatic.
- Calculations are carried out with the mass flow density of the air and water and not with the mass flows to disregard of the packing section.
- The charge losses are lower in the packed column. It can be assumed that the mass flow density of the air is constant. On the other hand, the evaporation rate is low, relative to the flow of the water used. It can be considered that the mass flow density of the water is constant throughout the packing.

• Water phase:

[Amount of energy stored in the volume element of height dz] = [(amount of heat carried away by the water during dt) − (amount of heat transmitted to the interface water–air during the same time interval dt)].

The heat balance of water in a volume element of packed bed with height dz and during time interval dt is given by the following equation:

Mathematically, this can be expressed as:

$$M_w C_{pw} \mathrm{d}T_l \mathrm{d}z = m_w C_{pw} \mathrm{d}T_l \mathrm{d}t - U_w(T_i - T_l)\mathrm{d}z\mathrm{d}t \quad (5)$$

It can be further simplified as:

$$\frac{\mathrm{d}T_l}{\mathrm{d}t} = \frac{1}{M_w C_{pw}}\left(m_w C_{pw}\frac{\mathrm{d}T_l}{\mathrm{d}z} - U_w(T_i - T_w)\right) \quad (5')$$

•Air phase:

[Amount of energy accumulated in the volume element of length dz] = [(amount of heat received by the interface water-air during the interval of time dt) − (Quantity of heat transmitted to the flow of air during the same time dt)].

The heat balance of air in a volume element of packed bed with length dz and during time interval dt is given by the following equation:

Mathematically, this can be expressed as:

$$M_a C_{pa} dT_a dz = U_a(T_i - T_a) dz dt - m_a C_{pa} dT_a dt \tag{6}$$

It can be further simplified as:

$$\frac{dT_a}{dt} = \frac{1}{M_a C_{pa}} \left(U_a(T_i - T_a) - m_a C_{pa} \frac{dT_a}{dz} \right) \tag{6'}$$

- Air–water interface:

[Amount of heat transmitted from the water current through the liquid film to the surface of the water-air separation] = [(amount of heat transmitted from the surface separation through the film gas to the gaseous stream) + (Quantity of heat applied to evaporate the amount of water transferred from the mass of liquid through the interface to the gas stream)].

At the air–water interface, heat balance can be written in the following form:

$$U_w(T_i - T_l) = U_a(T_i - T_a) + \lambda_o U_m(W_i - W_a) \tag{7}$$

The mass balance at the air–water interface is given by the following equation:

$$\frac{dW_a}{dt} = \frac{1}{M_a} \left(U_m(W_i - W_a) - m_a \frac{dW_a}{dz} \right) \tag{8}$$

To be numerically integrated, the above equations are completed with both empirical correlations of the voluminal heat coefficients (U_w, U_a) and mass transfer coefficient (U_m) which are obtained by Ben Amara et al. [21] and an algebraic equation of the curve of saturation of water steam [22]:

$$U_m = 0.6119 \times m_w^{0.1002} \times m_a^{0.3753} \times zl^{-0.0986}$$

$$U_w = 25223.5 \times m_w^{0.0591} m_a^{0.1644} \times zl^{-0.0542}$$

The air–film heat transfer coefficient and the mass transfer coefficient on the air–water interface are coupled by the Lewis relation as follows:

$$U_a = C_{pa} U_m$$

Stoecker and Jones [23] suggest that the system of equations developed and an additional equation of the absolute humidity of the air will be used to monitor the variation of different parameters at any point in the distiller.

The curve of saturation of water steam is given by the following equation:

$$W_i = 0.62198 \frac{P_i}{1 - P_i} \tag{9}$$

where P_i denotes the partial pressure of water vapor to the dry bulb temperature (atm), which is given by the following relationship:

$$P_i = \varphi P_{ws} \tag{10}$$

where φ and P_{ws} are, respectively, the relative humidity and the saturation pressure of water vapor in the air to the dry bulb temperature (atm).

The saturation partial pressure of water vapor in the air is given by the empirical relationship, simplified Keenan Kyes. This relation is valid for temperatures between 10 and 150°C.

$$\text{where} \quad \log\left(\frac{P_{ws}}{218,167}\right) = -\frac{\beta}{T_i}\left(\frac{a + b\beta + c\beta^2}{1 + d\beta}\right) \tag{11}$$

$$\beta = 647.27 - T_i$$
$$a = 3.2437814$$
$$b = 5.86823 \times 10^{-3}$$
$$c = 1.1702379 \times 10^{-8}$$
$$d = 2.1878,462 \times 10^{-3}$$

where

The evaporation coefficient of the basin to the glass cover is given by Malik et al. [24]:

$$h_{evp} = 16.273 \times 10^{-3} h_{cwv} \frac{P_w - P_v}{T_w - T_v} \tag{12}$$

The convection coefficient of the basin cover glass is calculated by Malik et al. [24]:

$$h_{cwv} = 0.884 \left[T_w - T_v + \frac{(P_w - P_v)(T_w + 273)}{268.9 \times 10^3 - P_w} \right]^{\frac{1}{3}} \tag{13}$$

The coefficient of heat transfer by convection between the basin and the water:

$$h_{cbw} = 135 \ \text{W/m}^2\text{K}$$

The radiation coefficient from the water to the glass is given by Dunkle [25]:

$$h_{\rm rwv} = \varepsilon_{\rm eff}\sigma \frac{\left[(T_{\rm w}+273)^4-(T_{\rm v}+273)^4\right]}{T_{\rm w}-T_{\rm v}} \quad (14)$$

$$\varepsilon_{\rm eff} = \left[\frac{1}{\varepsilon_{\rm w}}+\frac{1}{\varepsilon_{\rm v}}-1\right]^{-1} \quad (15)$$

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

$$h_{\rm cr} = h_{\rm cva} + h_{\rm rva} \quad (16)$$

$$h_{\rm rva} = \varepsilon_{\rm v}\, a \frac{\left[(T_{\rm v}+273)^4-(T_{\rm amb}+273)^4\right]}{T_{\rm v}-T_{\rm amb}} \quad (17)$$

Watmuff et al. [26] found that the convective heat transfer exchange coefficient between the outside of the glass and air is given by the following relationship:

$$h_{\rm cva} = 5.7 + 3.8V_{\rm wind} \quad (18)$$

4. Results and discussion

4.1. Numerical simulations in dynamic regime of solar still and solar water

Dynamic models obtained for the different stages of water distillation unit by solar energy are not represented usually by ordinary differential equations, but more often by partial differential equations of hyperbolic type from fluid mechanics involving time and space. It is, therefore, a difficult priority to exploit these systems as part of dynamic systems described by ordinary differential equations generally used automatically. These mathematical systems of infinite dimensions are called distributed parameter systems. Mathematics used the notions of infinity and continuous continuity. The exact solution of a problem of differential equations or partial drift is a continuous function. Computers know only the finite and discrete functions.

Faced with this problem, it is necessary to use approximation methods for the transformation of infinite-dimensional systems, consisting of partial differential equations in a finite-dimensional system formed by ordinary differential equations or recurrence equations. Among the many existing methods, we have chosen a relatively simple method to implement: the method of orthogonal collocation.

4.2. Numerical simulation of water solar collector

The numerical simulation in dynamic regime of behavior of the water solar collector is used to search the influence of the parameters mentioned below on the outlet temperature of the water ($T_{\rm w}$).

- Mass flow of water ($m_{\rm w}$).
- Inlet temperature of the water ($T_{\rm we}$).

Fig. 2 shows the influence of water flow on the variation of the water temperature at the outlet of the solar collector to the operating conditions for water presented under Fig. 2. This figure shows that the water temperature at the outlet of the sensor decreases when the flow rate of the water flowing through the solar collector water increases.

Fig. 3 shows the variation of the output fluid temperature $T_{\rm w}$ in function of the inlet temperature of

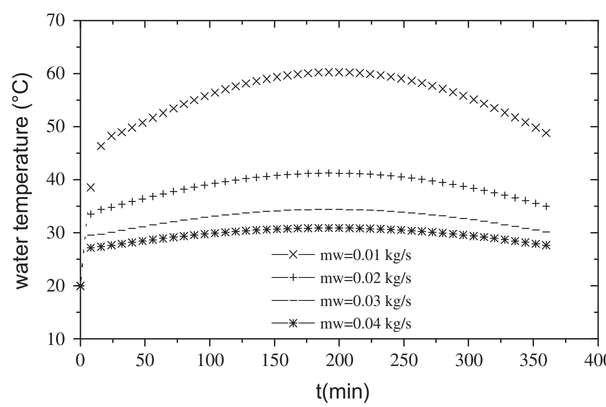

Fig. 2. Evolution of the water temperature at the outlet in function of time $T_{\rm amb} = 20$°C and $T_{\rm we} = 20$°C for different water flow.

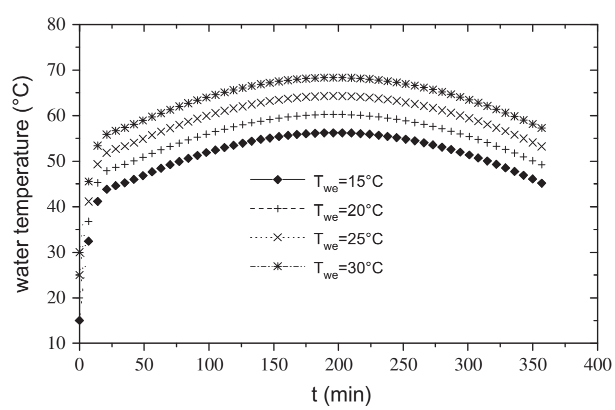

Fig. 3. The evolution of the temperature of the water at the outlet in function of time for different values of the temperature $T_{\rm we}$ of the inlet water $T_{\rm amb} = 20$°C and $m_{\rm w} = 0$ .01 kg/s.

water (T_{we}). However, the input fluid temperature (T_{we}) of the water solar is not always constant because it depends on the ambient temperature (T_{amb}).

The first observation that can be drawn from Fig. 3 is that for high values of T_{we}, T_w can have high values for example T_{we} equal to 20°C, T_w is the value of the order of 60°C, while for a value of T_{we} equal to 30°C, T_w is a value of the order of 69°C. So, from these results, we can conclude that it is interesting to work with high temperatures at the collector input to allow it to provide better performance.

4.3. Numerical simulation of solar distiller

Similarly, Fig. 4 shows the changes in water temperature T_w, the glass temperature T_v, and the basin temperature T_b of our device in the function of time. During a sunny day, the first thing that can be drawn from the figure that follows is that temperatures increase with the variation of the solar flux. The second point is that the water temperature and the absorber (pelvis) are almost the same because of contact with the last two heat transfer by convection directly.

We note that the output water temperature increases with the variation of the solar flux. This figure also shows that the output water temperature of water solar collector varies linearly with solar insolation. The temperature in the distiller has reached a temperature of 74°C as shown in Fig. 4; the temperature is mainly due to the effect of the preheater (solar water) and black basin with the aim of increasing the heat exchange surface and absorption of the radiation. In fact, this increase in temperature causes the heating of the preheated water inside the water tank (evaporation surface), resulting in a rise in temperature of the latter, and consequently an increase in condensation.

It is observed that the temperature at all points increases with increasing time until a maximum value at noon and begins to decline thereafter. This is due to the increase in the intensity of solar radiation in the morning and its decrease in the afternoon.

The rise in temperature of the glass T_v is due to the absorption by the glass incident solar radiation and the heat released by the surface evaporation (brine) radiation, evaporation, and convection. The temperature of the inner surface is slightly greater than the outside. This is due to the quantity of the flux received by the inner surface while the outer surface is subjected to the action of wind.

The tank temperature T_b absorbent is slightly larger than that of the brine T_w because of the characteristics of the absorber (high absorption coefficient), and heat loss through the base that are negligible as is indicated in Fig. 4.

Our solar still based on the greenhouse effect solar radiation heats the bottom of the black tank. The latter emits infrared heat salt water. The water evaporates and condenses on the glass. Salt therefore remains on the black background. Pure water drops runoff then into the chutes. Thus, filtered water is recovered in these channels (chutes).

The effect of water depth on the condensate produced is shown in Fig. 5 for a solar flux can reach almost 950 W/m^2. We see that the distillate flow increases with decrease in water depth. We can conclude that it is interesting to work with low water depths in the solar distiller to increase the production of distilled water. However, this amount is relatively small compared to other methods of distillation, but this disadvantage is offset by the fact that this method only requires sunlight to function.

Distilled water production varies from 0.1 to 0.5 kg in a daily radiation received on the plan and varying within a range from 600 to 950.81 W/m^2 at a temperature of basin which varies in the range of 30–55°C and temperature brine between 40 and 75°C. These results

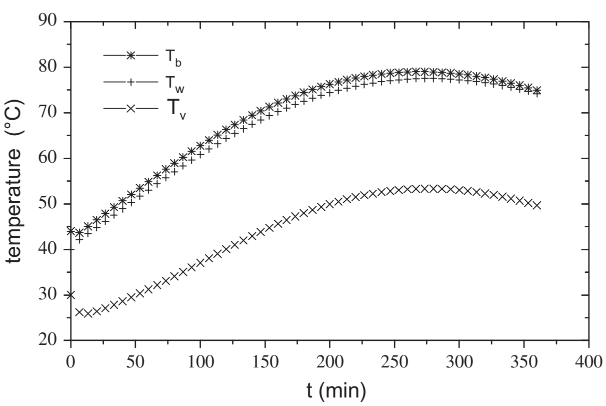

Fig. 4. Evolution of the temperature (T_w, T_v, T_b) in function of time T_{amb} = 15°C, T_{we} = 40°C, and T_{ve} = 30°C.

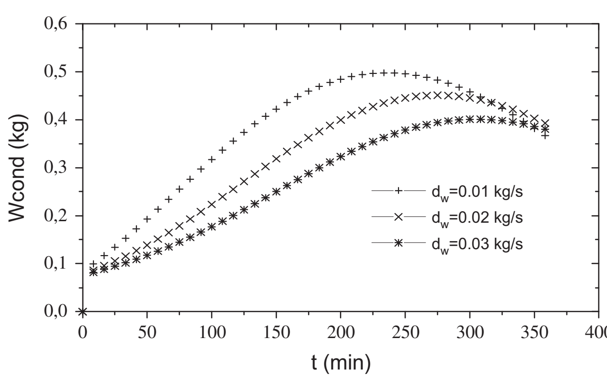

Fig. 5. Evolution of the amount of condensate (W_{cond}) in function of time for different water depth d_w: T_{amb} = 15°C, T_{we} = 40°C, and T_{ve} = 40°C.

which have been obtained by the theoretical method are almost the same as the experimental results Badran and AL- Tahaineh [27], which shows that the evolution of the thickness of the water layer causes the decrease in the production of distilled water.

Stcunanthan and Hansen [28] have also shown that the performance of the still increases when the distance between the brine and the distiller tank decreases. The thickness of the brackish water plays a very important role. Production is even more important for distiller with small thickness brine, but for a still with greater thickness of brine, the maximum production is observed shortly after sunset. Distillate production is an increasing function of the depth of the water table.

However, this growth is attenuated for values of the latter bases. This shows that the decrease in water brine has a positive effect on production.

We also note that these gaits that converge almost to the same point and which are due at the end of sunset to the intensity of solar flux are insufficient to visualize the phase difference between the three curves.

Fig. 6 shows that the temperature of the water is proportional to the water depth, and also that all the temperatures focus to the same point at the end of the execution time is it of the intensity of solar flux decreases at the end of the day and did not sufficiently highlight the difference of amplitude for the three temperatures.

Bilal et al. [29] and Kalidasa Murugavel et al. [30] found that the technique of adding the absorbent black material that is used in the basin with water (can store more amount of heat energy to increase the heat capacity of the basin and to increase the production night as quartzite, pieces of red bricks, pieces of concrete cement, lime stones and pieces of iron, etc.). In this section, we have studied the effect of material energy storage taking into account that the distiller is coupled with a preheating system (solar water).

For this study, we have used, as a heat storage material, sensitive pieces of cement concrete. The hourly production of distilled water for two types of distillers is shown in Fig. 7.

This production begins to be significant from 100 min of sunshine.

We find that the amount of distilled water produced from a distiller that contains materials energy storage is higher than the distiller without these latter.

The addition of energy storage materials in the solar still has an influence on the flow of water produced, but this flow varied according to the nature of

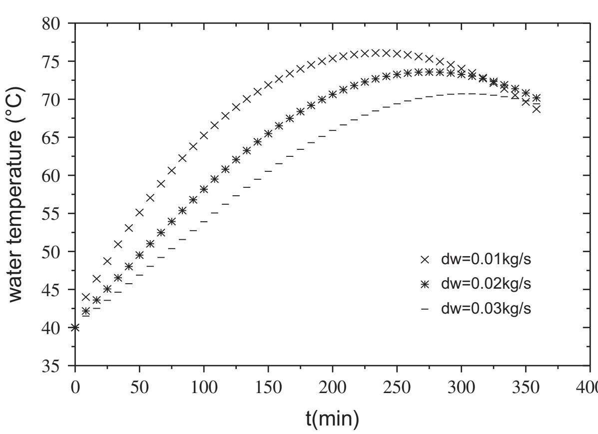

Fig. 6. Evolution of the water temperature in the output of distiller in function of time for different water depth (d_w): $T_{amb} = 15^\circ C$, $T_{we} = 40^\circ C$, and $T_{ve} = 30^\circ C$.

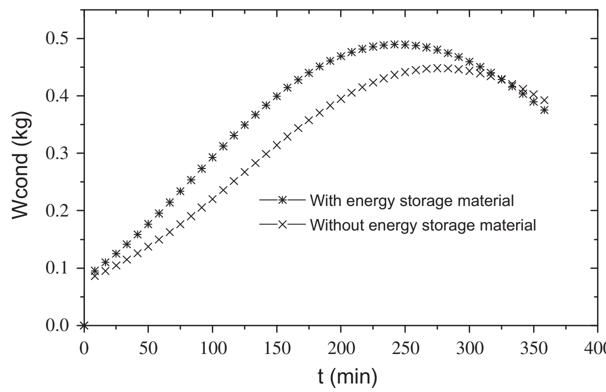

Fig. 7. Evolution of the amount of condensate in function of time with and without energy storage materials [$T_{amb} = 15^\circ C$, $T_{we} = 40^\circ C$, $T_{ve} = 40^\circ C$, $M_w = 20.5$ kg, Cem = 780 J/(kg K), $M_{em} = 22.65$kg, and $dw = 0.01$ m] Energy storage material: cement.

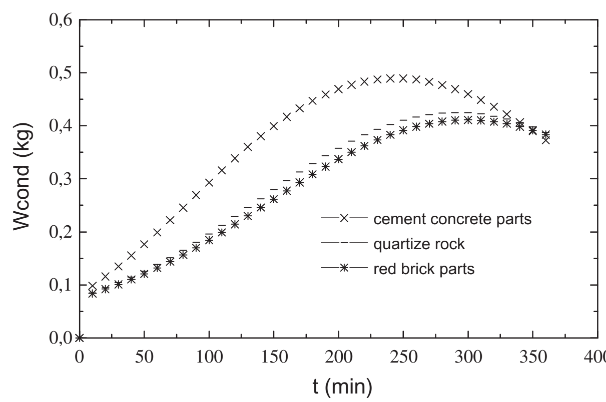

Fig. 8. Evolution of the amount of condensate in function of time for different energy storage material. [$T_{amb} = 15^\circ C$, $T_{we} = 40^\circ C$, $T_{ve} = 40^\circ C$ $M_w = 20.5$ kg $d_w = 0.01$ m, Cem cement = 780 J/(kg K) Mem = 22.65 kg, Cem red brick = 840 J/(kg K) Mem = 22.65 kg, Cem quartzite rock = 775 J/(kg K) Mem = 39.9 kg.

the added materials as shown in Fig. 8 after a numerical simulation and this is due to the heat capacity of each material.

4. Conclusion

The work presented in this article concerns the theoretical and numerical study of a new solar still in dynamic mode. The results of this study are an important contribution to the enrichment of the literature relating to the work on desalination by distillation. We have devoted our efforts to model a water desalination unit in a dynamic regime. The simulation allowed us to predict the behavior of the solar still and solar water collector in function of variations on internal variables of the system and in function of metrological variations.

The unit consists of a conventional solar still with energy-storing materials and coupled with an external heat source and condenser device. The effects of incorporating the different modules on the system performance were studied. For all configurations, modeling of the system and simulating its behavior have been successfully done on the basis of thermal and mass balances approach. Based on theoretical simulations, the proposed unit would perform much better than a conventional solar still.

The obtained results show the influence of external and internal parameters on the operating characteristics of the solar still, in particular the production and performance. It appears in particular an increase in global solar irradiation which remains the most influential parameter leads to an increase in these characteristics.

The solar still has been theoretically modeled and tested for different energy-storing materials and different water depths. Theoretically, the maximum values of production rate, water temperature, and glass temperature are varying inversely with heat capacity of basin water and other materials used in the basin. The total production also decreases with the increase of basin heat capacity.

Nomenclature

C_w — water heat capacity in the solar water [J/(kg K)]
C_a — air heat capacity in the solar still [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 packed bed [kg/s]
M_a — air mass flow density in the solar distiller [kg/(m^2 s)]
M_v — glass cover weight [kg]
M_w — water weight in the solar distiller [kg]
M_{st} — storage material weight in the solar distiller [kg]
C_{st} — storage material heat capacity in the solar still [J/(kg K)]
M_b — absorber weight of solar water [kg]
T_i — temperature at the air–water interface (packed bed) [°C]
U_{loss} — global exchange coefficient between the absorber of the solar distiller and the external environment [W/(m^2 K)]
W_a — air humidity in the solar distiller (packed bed) [kg water/kg dry air]
W_i — saturation humidity in the solar distiller [kg water/kg dry air]
U_w — global exchange coefficient of the absorber of the solar water with the outside environment [W/(m^2 K)]
T_b — temperature of the absorber Basin distiller [°C]
T_a — air temperature in the solar distiller [°C]
T_v — glass cover temperature of the solar distiller [°C]
T_{amb} — ambient temperature [°C]
T_w — water temperature in the solar water [°C]
d_w — water depth [m]
T_{ve} — the input water temperature [°C]
T_{we} — the input glass cover temperature [°C]
M_{em} — energy storage material weight in the solar distiller [kg]
C_{em} — energy storage material heat capacity in the solar distiller [J/(kg K)]
p_w — vapor pressure at T_w [atm]
p_v — vapor pressure at T_v [atm]
V_{wind} — wind speed
U_m — mass transfer coefficient of water vapor to the air-water interface [W/(m^2 K)]
U_w — heat exchange coefficient of the water film in the packed bed [W/(m^2 K)]
U_a — heat exchange coefficient of the air film in the packed bed [W/(m^2 K)]
Z_l — the packed bed height (mm)
C_{pa} — air heat capacity in the packed bed [J/(kg K)]
T_l — temperature at the packed bed [°C]

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 — Steaffan-Boltzman constant

ε_e — water emissivity
ε_v — glass cover emissivity

Subscripts

amb — ambient
a — air
w — water
loss — loss to ambient
v — glass cover
b — basin
st — storage material

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