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Effects of the simple/double glass cover use and the orientation of a simple solar still on operating parameters

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ABSTRACT

Evaluation of inner glass, outer glass water and basin temperatures as well as yield of a simple solar distiller (SSD) still is performed. Numerical computation based on the Runge-Kutta method is used. Experimental results and those calculated are then compared in terms of the above-mentioned parameters. Results concern the climatic conditions of Gabès (south east region of Tunisia). Effects of different parameters, namely the orientation and the use of single or double glass cover of the SSD still are studied. It is important to notice the significant effects on daily yield due to the studied operating parameters. It was found that the double glass cover use provides higher values of temperatures as well as the still productivity.

Keywords: Theoretical temperature; Simple Solar Distiller (SSD); Yields

1. Introduction

Enhancement of fresh water productivity obtained by solar stills can be reached via the improvement of the solar desalination technology. The effect of climatic conditions, the design of the stills, the operational conditions and the geographical location can be regarded as the most important operating parameters for water productivity. Mousa et al. [1] studied the modelling and performance analysis of a single-basin solar still with the entering brine flowing between a double-glass glazing. The objective of this arrangement is to lower the glass temperature and thus to increase the water-to-glass temperature difference. The results show that the relative performance of the stills depends on the level of the used insulation. The hourly and daily productivities of the stills and the temperatures of the water and the glass covers were also predicted under the meteorological conditions. Al-Hinai et al. [2] used a mathematical model to predict the productivity of a simple solar still under different climatic, design and operational parameters. The energy balance equations have been written considering the effects of conduction, convection, radiation, evaporation and ventilation in a greenhouse fish pond [3]. The governing equations are numerically solved with Matlab 7.0 software to predict the water temperature. A parametric study has also been performed to find the effects of various parameters, namely the number of air changes per hour, the transmissivity and the isothermal mass and height of the greenhouse. It was observed that there is no significant effect of the parametric study on water temperature due to the larger isothermal mass. The studied model has been validated with experimental data. Statistical analysis shows that the predicted and experimental values of water temperature exhibited fair agreement with a coefficient of correlation $r = 0.90$ and a square root of mean percent deviation $e = 1.67\%$. Expressions for water and glass temperatures, hourly yield and instantaneous

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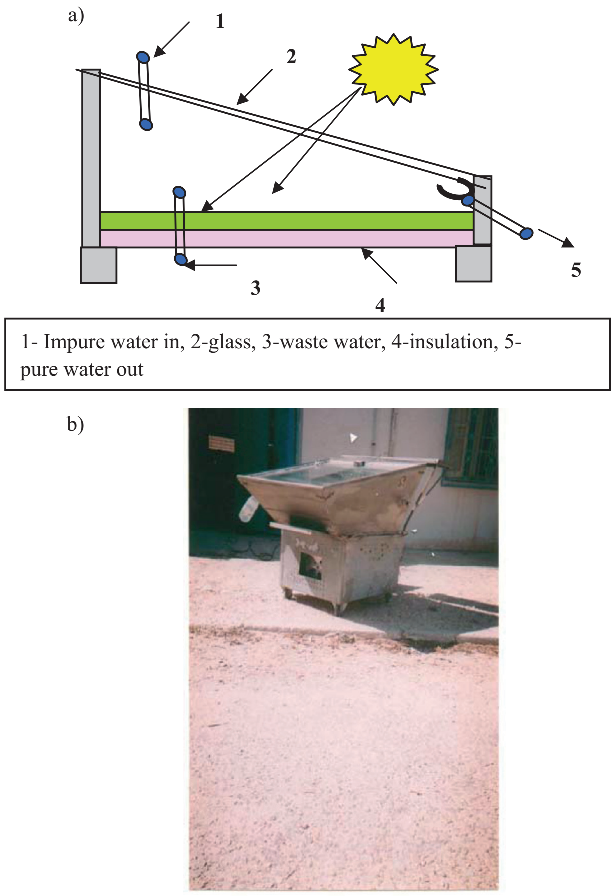

Photograph of the SSD still

Fig. 1. Simple solar distiller still (SSD): (a) schematic diagram of the still and (b) photograph of the still.

efficiency for double slope solar distillation systems have been analytically derived by Shailendra et al. [4]. The analysis is based on the energy balance for the systems. A thermal model has been developed to predict the performance of the still based on both, the inner and the outer glass temperatures of the solar still. It was concluded that there was a significant effect of operating temperature ranges on the internal heat transfer coefficients. By considering the inner glass cover temperature, there was a reasonable agreement between the experimental and predicted theoretical results. Mathematical models that can predict the hourly distillate productivity are developed by Sadineni et al. [5]. Calculated results are in good agreement with those obtained experimentally. Productivity of the weir-type still with a single-pane glass is also compared with conventional basin types tested at the same location. The productivity of the weir-type still is approximately 20% higher. The quality of distillate from the still is analyzed to verify the ability of the still to meet the standards required by the electrolyses. El-Sebaii [6] analytically solved the energy balance equations by using the eliminations technique for various parts of solar pond. In order to validate the theoretical model, experiments are performed under the batch mode of heat extraction with a black painted baffle plate made of stainless steel, with and without vents in the plate, for different masses of water in the upper and the lower layers. It was found that the pond-water temperature decreases with increasing vent area. Experiments have also been carried out using baffle plates made from aluminium and mica in order to study the effect of the thermal conductivity of the baffle plate on the pond's performance. The average temperature of the pond water was found to be less dependent on the thermal conductivity of the baffle plate. It was also inferred that the present system could provide 88 liters of hot water at a maximum temperature of 71°C with a daily efficiency of 64.3% when the baffle plate was used without vents. Comparisons between experimental and theoretical results showed that the theoretical model could be used for estimating the ponds performance with good accuracy.

In the present study, the influence of some operating parameters namely, the orientation and the use of a single or a double glass cover of a simple solar still on fresh water yield and on inner glass, outer glass water and basin temperatures is numerically determined. Theoretical results are then compared with those obtained experimentally. It is important to notice that the studied region (Gabès region which is located in south east of Tunisia) suffers from fresh water scarcity.

2. Experimental set up

2.1. The Simple Solar Distiller (SSD) model

In the SSD model, water output is simply obtained by purely solar energy. This model works only on day. Fig. 1 shows the schematic diagram of the SSD and its photograph still. It consists of a basin which is fabricated from fiber forced plastic material that accommodates the brackish water, and is covered by a slopping cover. The height of the lower vertical side of solar still is kept constant at 60 cm and the area of the basin is equal to 0.4 m^2. The operation of the still is very simple: the incident solar radiation is transmitted through the transparent glass cover to the water. As a result, the water is evaporated, then reached the glass cover and finally collected at the distilled water gutter at condensed phase.

2.2. Experimental parameters

- For the glass cover: the value (0) is given when a single glass cover is used and the value (1) for a double glass cover gives by Table.

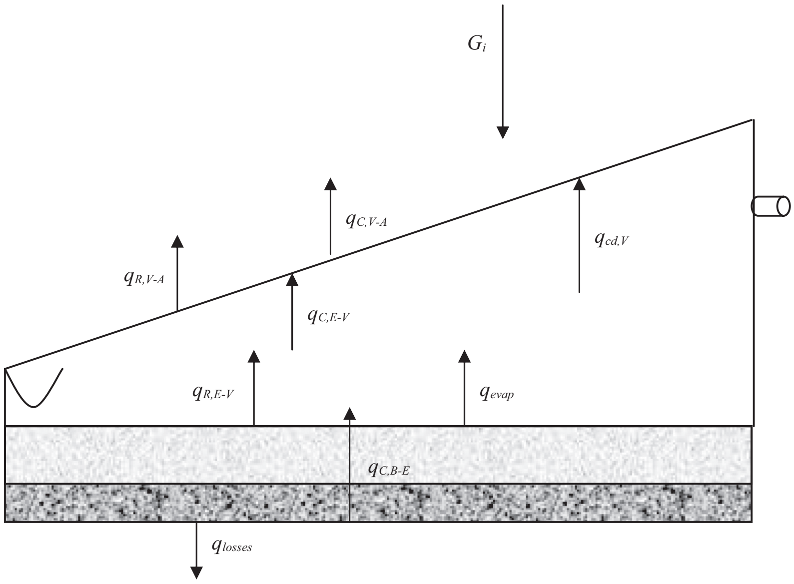

Fig. 2. Illustration of the overall energy balance.

- For the still: the value (0) is given for a fixed orientation towards the south, the value (1) is given when the still is periodically oriented towards the sun (azimuth consideration).

External, inner, water and basin temperatures are measured by using sondes while distiller output water temperature is measured by a mercury thermometer. The distiller output is measured by a graduated test-tube. The temperatures and yield are measured every hour for the four configurations.

3. Energy and mass balance equations

The performance of a solar still is generally expressed as the quantity of evaporated water per unit area of the basin in one day. This quantity is given in cubic meter or liter. The performance can be predicted by resolving the energy and mass balance equations that depend on the different components of the still. The thermophysical properties of the fluid and the still are considered constant. Fig. 2 shows a simplified model of various heat fluxes of the studied still.

3.1. Energy balance of the outer glass cover

$$\frac{m_v C_{pV}}{S_v}\frac{\mathrm{d}T_{\mathrm{ext}}}{\mathrm{d}t} = \alpha_v(1-\phi_v)G_i - q_{R,V-A} - q_{C,V-A} + q_{cd,v} \quad (1)$$

where:

$$m_v = \rho_v Vo_v = \rho_v S_v e_v \quad (2)$$

V_{ov} is the glass cover volume

Substituting Eq. (2) into Eq. (1) gives:

$$\frac{\mathrm{d}T_{\mathrm{ext}}}{\mathrm{d}t} = \frac{1}{(\rho_v e_v C_{pV})}\left[\alpha_v(1-\phi_v)G_i - q_{R,V-A} - q_{C,V-A} + q_{cd,v}\right] \quad (3)$$

Appendix A gives the expressions of $q_{R,V\text{-}A}$ and $q_{C,V\text{-}A}$.

3.2. Energy balance of the inner glass cover

The energy equation of the inner glass cover can be written as:

$$\frac{m_v C_{pV}}{S_v}\frac{\mathrm{d}T_{\mathrm{int}}}{\mathrm{d}t} = q_{R,E-V} + q_{C,E-V} + q_{\mathrm{evap}} - q_{cd,v} \quad (4)$$

By substituting Eq. (2) into Eq. (4) we get:

$$\frac{\mathrm{d}T_{\mathrm{int}}}{\mathrm{d}t} = \frac{1}{(\rho_v e_v C_{pV})}\left[q_{R,E-V} + q_{C,E-V} + q_{\mathrm{evap}} - q_{cd,v}\right] \quad (5)$$

Appendix B gives the expressions of $q_{R,E-V}$, $q_{C,E-V}$ and q_{evap}.

3.3. Energy balance of the water

$$\frac{m_E C_{pE}}{S_E}\frac{\mathrm{d}T_W}{\mathrm{d}t} = (1-\alpha_v)(1-\phi_v)\alpha_E G_i + q_{C,B-E} - q_{R,E-V} - q_{\mathrm{evap}} - q_{C,E-v} \quad (6)$$

where

$$m_E = \rho_E Vo_E = \rho_E S_E e_E \quad (7)$$

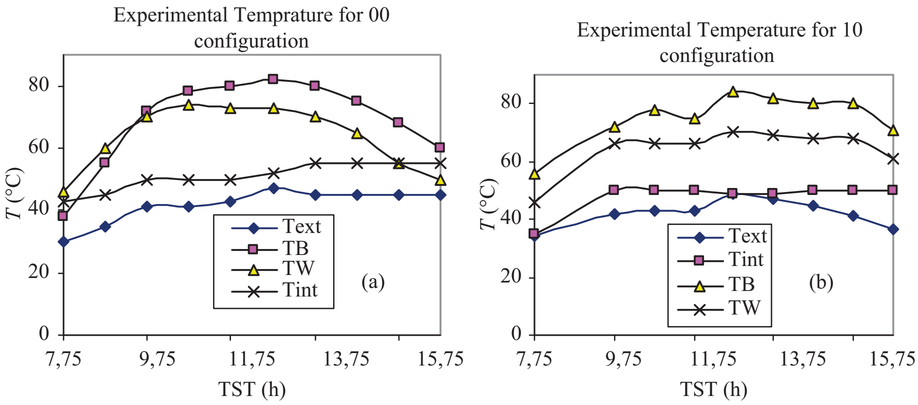

Fig. 3. Hourly measured temperatures: (a) ''00'' configuration, (b) ''10'' configuration.

where Vo_E and e_E are the volume and the thickness of water

Substitution of Eq. (7) into Eq. (6) gives:

$$\frac{dT_W}{dt} = \frac{1}{(\rho_E C_p E e_v)}[(1-\alpha_v)(1-\phi_v)(1-\alpha_E)\alpha_E G_i + q_{C,B-E} - q_{R,E-V} - q_{\text{evap}} - q_{C,E-V}] \quad (8)$$

The expression of $q_{C,B-E}$ is given by Appendix C.

3.4. Energy balance of the basin

$$\frac{m_B C_{pB}}{S_B}\frac{dT_B}{dt} = (1-\alpha_v)(1-\phi_v)\alpha_B G_i + q_{C,B-E} - q_{\text{losses}} \quad (9)$$

where

$$m_B = \rho_B \times Vo_B = \rho_B \times S_B \times e_B \quad (10)$$

V_{OB} and e_B are the volume and the thickness of the basin, respectively. Thus:

$$\frac{dT_B}{dt} = \frac{1}{(\rho_B C_p B e_B)}[(1-\alpha_v)(1-\phi_v)(1-\alpha_E)\alpha_B G_i - q_{C,B-E} - q_{\text{losses}}] \quad (11)$$

Appendix D gives the expression of thermal losses.

4. Resolution of system of equations

A computer program written in MATLAB for the resolution of the above set of equations using the 4th-order Runge–Kutta method was developed. Theoretical values of water, inner glass, outer glass basin temperatures and the yields are then calculated by providing the initial values of water and glass temperatures and the effective solar intensity.

The theoretical investigation of the solar still is carried on under the following assumptions:

- One-dimensional heat transfers.
- Thermal loss of water supplement is neglected.
- Thermal loss of insulator is neglected: adiabatic wall.
- Thermal loss of distillate extraction is neglected.
- Thermal loss of water vapor is neglected.
- Speed of the wind is considered constant.

5. Results and discussion

Figs. 3 and 4 show the hourly variations of the measured temperature concerning the four studied configurations (Table 1). Generally speaking, temperature decreases in the following order: $T_B > T_W > T_{\text{int}} > T_{\text{ext}}$. Water temperature is higher than inner and outer glass cover temperatures since solar energy is absorbed there. Maximum water temperature occurs between hours 12 and 14 h. For fixed still positions (i.e. ''00'' and ''10'' configurations), the higher temperature values occurred between 11.75 and 13.75 h. In this case, outer glass cover temperature ranges between 35 and 40°C for single cover use (i.e. '00' configuration, while it ranges between 38 and 45°C for double cover use (i.e. '10' configuration). During all the period of time, temperature difference between inner and outer glass cover is smaller for the case of double glass cover as compared to that of single cover. This difference becomes practically equal to zero at time TST = 12 h for the case of double cover utilisation (see Fig. 4(b)), inducing maximum heat transfer between basin and water since maximum water temperature is obtained at this time and it is about 70°C. The use of double glass cover induces the decrease of thermal losses, as a consequence, water temperature will increase. In this case, water

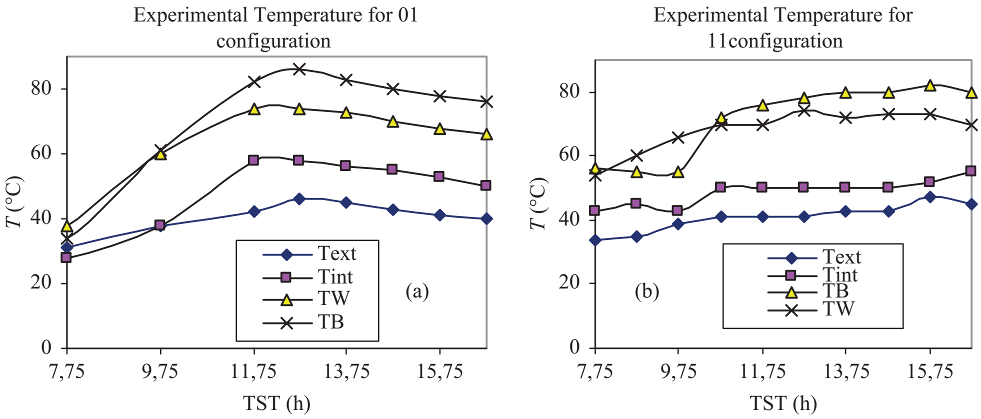

Fig. 4. Hourly measured temperatures: (a) ''01'' configuration, (b) ''11'' configuration.

temperature profile shows that its value ranges between 65 and 70°C during the measured period of time ranging between 9.75 and 15.75 h for the case of double glass cover use (see Fig. 3(b)). For the same period of time, this value fluctuates between 50 and 70°C when a single glass cover is used (see Fig. 3(a)). For an oriented still position (i.e. '01' and '11' configurations), Figs. 4(a) and 4(b) show that maximum values of temperature are obtained between the hours 9.75 and 13.75 h. In this case, maximum value of outer glass cover reaches 40°C, while that of inner glass is about 50°C. From Fig. 4(b), a small difference between the basin and water temperatures is obtained. This is due to the high value of convective heat transfer from the basin to the mass of water when double glass cover is used. This was indicated by Hidouri et al. [7]. Oriented still with double glass cover gives water temperature approximately around 70°C for a long period of time (from 10 h to 15 h75 as illustrated in Fig. 4(b)).

As an important conclusion, the use of double glass cover, as compared to the single cover use, induces the reduction of the temperature difference between inner and outer glass covers, which causes the increase of heat transfer from basin surface to water. As a consequence an increase in water temperature is obtained. The use of double glass cover with oriented still gives the highest water temperature (i.e. '11' configuration).

Table 1
The four studied configurations

Glass cover	Position	Configuration
0	0	00
0	1	01
1	0	10
1	1	11

For comparison purposes, Figs. 5(a) and 5(b) show the calculated temperature by using the energy balance equations as defined above. As the experimental case, the temperature decreases in the following order: $T_B > T_W > T_{\text{int}} > T_{\text{ext}}$. The theoretical temperature values have the same trends. On the other hand, the experimental glass cover temperature values are higher than those calculated. This is due to the fact that the values of the temperature measured by the thermocouples are higher than the real values. This temperature difference can be explained by the increased temperature of the thermocouple covers which are exposed to the sun.

From Fig. 6, the yields increase with the temperature, a declining trend is observed during off-sunshine due to the decreased water temperature. The use of the double glass cover provides better daily yields as compared to the single cover. This is due to the fact that basin water temperature is higher for the case of double glass cover use as compared to the single cover case as mentioned above. The temperature difference between water and basin is smaller for the case of double glass cover use, this induces heat transfer increase of water, and consequently, the augmentation quantity of evaporated water.

Fig. 7 shows the calculated values of the solar still yields. Deviations between experimental and theoretical values result in the main following reasons: the governing equations used in the calculation do not consider thermal losses due to the leakage of the saturated water from the still. The use of rubber band could not prevent thermal losses. The vapor pressure and the saturated air can escape to the outside. The coming air from the outside to the still is less saturated, and it takes some time to be saturated after heating. For all these reasons, the experimental solar still productivity decreases. Consequently, the calculated values of the yields are higher than those obtained experimentally.

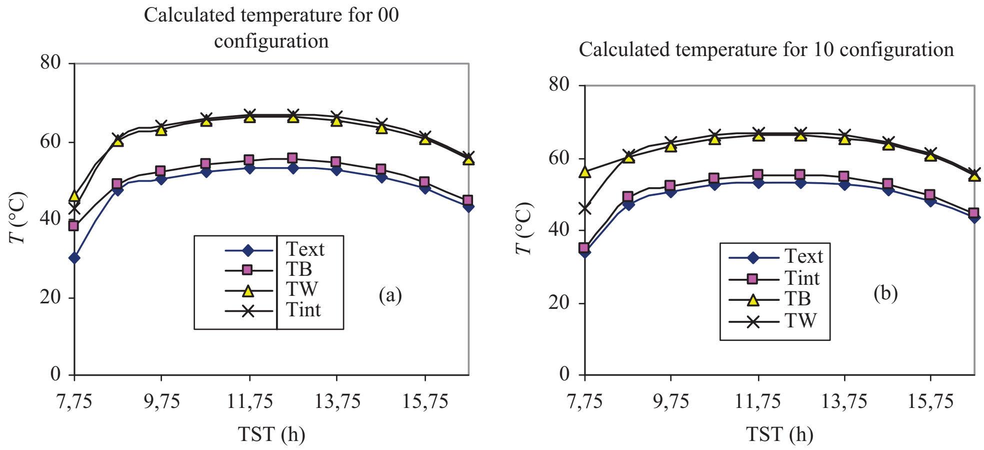

Fig. 5. Hourly calculated temperatures: (a) '00' configuration, (b) '10' configuration.

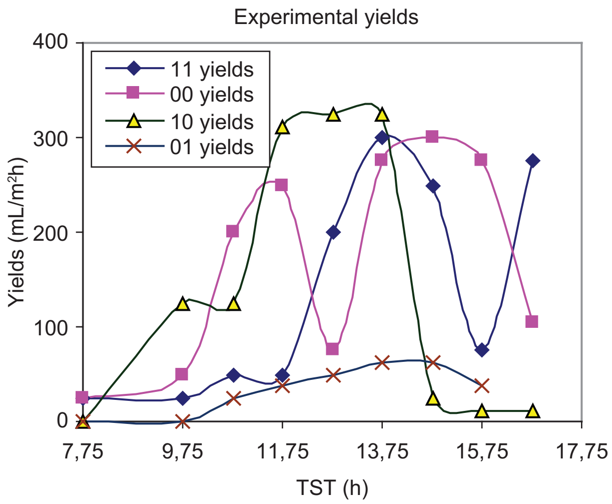

Fig. 6. Experimental output for the four configurations.

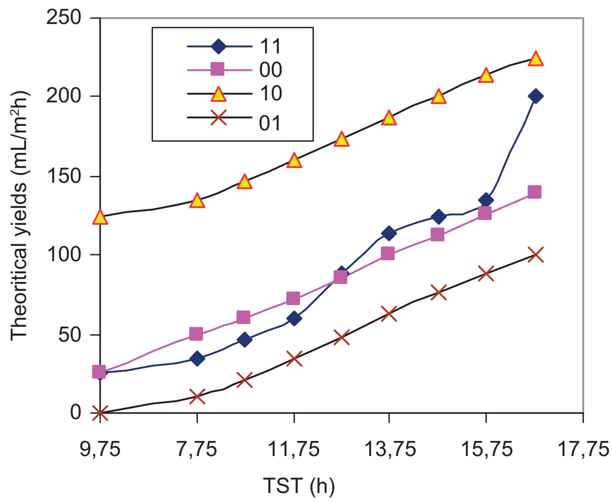

Fig. 7. Calculated output of the studied configurations.

6. Conclusion

The effects of single or double glass cover utilization and the orientation of a simple solar still on operating temperatures and yields are experimentally determined and numerically calculated. Double glass cover use shows higher values of water temperature and still productivity. Higher value in terms of the yields is obtained for the '10' configuration which is about 350 mL/m^2 h. The numerical model indicates the same behaviors as the experimental findings with some differences in temperature profiles and yields. This is due to the simplified hypotheses that are considered, especially the neglected thermal losses and the incoming air to still that causes the decrease in experimental yields.

Appendix A: Expressions of $q_{R,V-A}$ and $q_{C,V-A}$.

$$q_{R,V-A} = h_{R,V-\text{sky}}\left(T_{\text{ext}} - T_{\text{sky}}\right) \tag{A.1}$$

The coefficient of exchange by radiation $h_{R,V-\text{sky}}$is given by:

$$h_{R,V-\text{sky}} = \frac{\varepsilon_v \sigma \left[\left(T_{\text{ext}}\right)^4 - \left(T_{sky}\right)^4\right]}{\left(T_{\text{ext}} - T_{\text{sky}}\right)} \tag{A.2}$$

$$q_{C,V-A} = h_{C,V-A}(T_{v\text{ext}} - T_A) \tag{A.3}$$

The convective heat transfer coefficient between the external face of the glass cover and outside is given by the following relation [7]:

$$h_{C,V-A} = 5.7 + 3.8V \tag{A.4}$$

The temperature of the sky is given by [8]: $T_{sky} = T_A - 12$, T_A is the ambient temperature.

Appendix B: Expressions of $q_{R,E-V}$, $q_{C,E-V}$ and q_{evap}

$$q_{R,E-V} = h_{R,E-V}(T_W - T_{int}) \quad (B.1)$$

where

$$h_{R,E-V} = \frac{\varepsilon_{eff}\sigma\left[(T_W)^4 - (T_{int})^4\right]}{(T_W - T_{int})} \quad (B.2)$$

$$\varepsilon_{eff} = \left[\frac{1}{\varepsilon_V} + \frac{1}{\varepsilon_W} - 1\right]^{-1} \quad (B.3)$$

$$q_{C,E-V} = h_{C,E-V}(T_W - T_{int}) \quad (B.4)$$

$h_{C,E-V}$ is given by:

$$h_{C,E-V} = 0.884\left[T_W - T_{int} + \frac{(P_W - P_{int})(T_W)}{(268.9 * 10^3 - P_W)}\right]^{1/3} \quad (B.5)$$

The expression of the saturated vapor pressure P (in Pa) is given by [9]:

$$P = \exp\left[25.317 - \left(\frac{5144}{T}\right)\right] \quad (B.6)$$

Suppose that the quantity of heat during the evaporation of the water per unit of time and surface is equal to the quantity of heat of condensation released per unit of time and surface on the internal face of the glass. That is:

$$q_{evap} = h_{evap}(T_W - T_{int}) \quad (B.7)$$

The evaporation coefficient is given by [9]:

$$h_{evap} = 8.314 * 10^{-3} h_{C,E-V}\left[\frac{(P_W - P_{int})}{(T_W - T_{int})}\right] \quad (B.8)$$

Appendix C: Expression of $q_{C,B-E}$

$$q_{C,B-E} = h_{C,B-E}(T_B - T_W) \quad (C.1)$$

where

$$h_{C,B-E} = \frac{Nu * \lambda_E}{l} \quad (C.2)$$

***Nu* is the Nusselt number. In this kind of problem *Nu* is given by:**

$$Nu = c * (Gr * Pr)^n \quad (C.3)$$

c and n are constant and depend on the geometry of the system and nature of the flow (i.e. laminar or turbulent). In the case of a horizontal plate in laminar flow, Nusselt number is given by [10]:

$$Nu = 0.27 * (Gr * Pr)^{0.25} \quad (C.4)$$

Grashof number is defined as follows:

$$Gr = \frac{\beta g \rho_E^2 l^3 \Delta T}{\mu_E^2} \quad (C.5)$$

$\triangle T = T_W - T_{int}$ is the temperature difference between inner and outer glass cover.

Prandtl number is given by:

$$Pr = \frac{\mu_E C_{PE}}{\lambda_E} \quad (C.6)$$

The heat released during evaporation is given by:

$$q_{evap} = \dot{m}_d * L_V \quad (C.7)$$

By equating equations (B.7) and (C.7), we get:

$$\dot{m}_d = \frac{h_{evap}(T_W - T_{int})}{L_V} \quad (C.8)$$

Appendix D: Expression of q_{loss}

q_{losses} is the thermal loss of the basin by thermal conduction through the insulation, it is given by the following expression *[11]:*

$$q_{losses} = U\Delta T \quad (D.1)$$

U is the global coefficient of heat exchanged, it is given by:

$$U = \frac{1}{\left(\frac{th_{\text{ins}}}{k_{\text{in}} * S_B} + \frac{1}{h_a * S_B}\right) S_B} \quad \text{(D.2)}$$

Symbols

C_{pB}	isobaric specific heat of basin, J/(kg K)
C_{pE}	isobaric specific heat of water, J/(kg K)
C_{pV}	isobaric specific heat of absorber glass, J/(kg K)
e_V	glass thickness, m
g	gravitational acceleration, m/s^2
G_i	total incident solar radiation, W/m^2
h_a	convective heat transfer coefficient between the glass cover and outside, W/(m$^{2\circ}$C)
$h_{C,B-E}$	convective heat transfer coefficient between the bottom of the basin and the water, W/(m$^{2\circ}$C)
$h_{C,E-V}$	convective heat transfer coefficient between the water and the glass, W/(m$^{2\circ}$C)
$h_{C,V-A}$	convective heat transfer coefficient between the glass and the ambient conditions, W/(m$^{2\circ}$C)
h_{evap}	heat transfer coefficient by evaporation-condensation between the water and the glass, W/(m°C)
$h_{R,E-V}$	radiative heat transfer coefficient between the water film and the glass, W/(m$^{2\circ}$C)
$h_{R,V-\text{sky}}$	radiative heat transfer coefficient between the glass and outside, W/(m$^{2\circ}$C)
k_{in}	thermal conductivity of the insulation, W/(m°C)
L_V	latent heat of vaporization of sea water, J/kg
l	longitude, degree
m_B	mass of basin, kg
m_d	mass of distilled water, kg
$\dot{m}_d$	hourly calculated yields, kg/(m^2 h)
m_E	mass of water, kg
m_v	mass of absorber glass, kg
$q_{C,B-E}$	convective heat transfer flux between the basin and the water, W/m^2
$q_{C,E-V}$	convective heat transfer flux between the water and the glass, W/m^2
$q_{cd,v}$	conduction heat transfer flux through the glass cover, W/m^2
$q_{C,V-A}$	convective heat transfer flux between the glass and air, W/m^2
q_{evap}	evaporative heat transfer flux, W/m^2
$q_{R,E-V}$	radiative heat transfer flux between the water and the glass, W/m^2
$q_{R,V-A}$	radiative heat transfer flux between the glass cover and air, W/m^2
S_B	basin area, m^2
S_E	area of water, m^2
S_v	area of glass cover, m^2
T_B	basin temperature, °C
T_{ext}	outer glass cover temperature, °C
th_{ins}	thickness of the insulation, m
T_{int}	inner glass cover temperature, °C
T_{sky}	sky temperature, °C
TST	True Solar Time, h
T_W	water temperature, °C
V	speed of the wind, m/s

Greek letters

α_B	absorptivity of basin
α_E	absorptivity of water.
α_v	absorptivity of the absorber glass
β	thermal expansion coefficient, $\beta = \frac{1}{\frac{(T_B + T_w)}{2}}$, K^{-1}
ΔT	temperature difference between water temperature and mixture of air and water vapor, °C
ϵ_{eff}	effective emissivity
ϵ_V	glass cover emissivity
ϵ_w	water emissivity
φ_V	coefficient of reflexion of the glass
λ_E	thermal conductivity of water, W/(m.K)
μ_E	dynamic viscosity of water, kg/(m.s)
ρ_V	density of glass cover, kg/m^3
ρ_E	density of water, kg/m^3
σ	constant of Stefan-Boltzmann

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