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RESEARCH ARTICLE OPEN ACCESS

Theoretical and Experimental Study of the Solar Still Coupled To a Vertical Still with Water Film

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ABSTRACT

Solar distillation is one of the simplest processes and the most significant of separation. A solar distiller of new design was built by the coupling of two confused devices which are; a conventional solar distiller with only one slope directed towards the south, with what we name a Solar Still with Capillary Film (or SSCF); It consists of a parallelepipedic compartment formed by two plates opposite face to face and drawn aside from a distance from 0.03m, which devote an advantage of re-use of the condensation latent heat to evaporate another quantity of water. We developed a digital code which makes it possible to obtain the values of the temperatures and the rate of condensation of this devise. In this work we consider the comparative study between the theoretical results, and those measured in experiments. We numerically found a rate of condensation very important which reaches 8,43Kg.m^{-2}.d^{-1}, and which approaches to that obtained in experiments, in sunny day (correspondent at 06/8/2007), and a solar radiation of 20,7 MJ.m^{-2}.d^{-1}.

Keywords - solar energy, solar distillation, Solar Still with Capillary Film, modeling, simulation.

I. INTRODUCTION

Several studies on the solar distillers of various designs were carried out theoretically and in experiments in order to determine their distillate productivity and the productivity dependence on the weather parameters, of design and operation re-examined by Malik et al [1], and Tanaka et al [2], Bouchekima et al [3]. Our study relates to the experimentation and the modeling of a solar distiller with a new configuration is built of two distiller types: it is a traditional solar distiller with greenhouse effect and a distiller with Capillary Film (or SSCF) [4], and aims at an improvement of its yield for a distillation of brackish water.

Brackish water is non-drinkable but saline water, of salinity (S≥2,5 g.L^{-1}) lower than that of sea water but which is far away from the World Health Organization standards (WHO). Solar distillation seems as a solution to reduce this salinity, and it is interesting in particular for the arid or isolated distant areas.

Our experimental work was carried out at Ouargla, south Algeria (latitude; 31,95°N, longitude; 5,32°E, and altitude; 141m), the average potential of solar radiation which is available in this area exceeds 20,7 MJ.m^{-2}.d^{-1}, and the daily average insolation is 8.1 hours over all the year [3].

Cooper and Appleyard [5] built and examined a distiller in three effects type composed of a glass cover above. The wicks soaked with saline water were in contact with the bottom of the absorption plate and parallel plates except the lower plate.

The distiller was inclined so that the plate evaporator faces to the top with the sun and received solar energy. The steam evaporated wick soaked with saline water, spread through space in bottom and is condensed on the higher face of the last plate. The condensation latent heat is communicated to the plate evaporator and the soaked wick which causes the evaporation of water in the second cell. In this manner the condensation latent heat is recovered and re-used to increase the distillate total quantity. Tanaka et al [6], E1-Bahi et al [7], Toure et al [8], Tanaka et al [9], and Bouchekima et al [3], all thorough studies of this type of multiple effect which developed by Cooper and Appleyard.

II. THE DEVICE DESCRIPTION

The device consists of two different cells whose first is a traditional solar still, composed of a rectangular basin dyed in black overcome by a layer of brackish water for evaporation, and covered with a transparent glazing in order to make pass the solar rays inside the system.

The glass cover inclination angle depends on the second cell height which consists of two opposite plates forming a parallelepipedic. The evaporated water flow runs out slowly under the effect of capillarity, on a fabric piece adherent the evaporation plate. The produced water steam leaves the fabric towards the cold wall. The produced distilled water and the residue are gathered in collectors. The Fig 1 shows the device functioning principle.

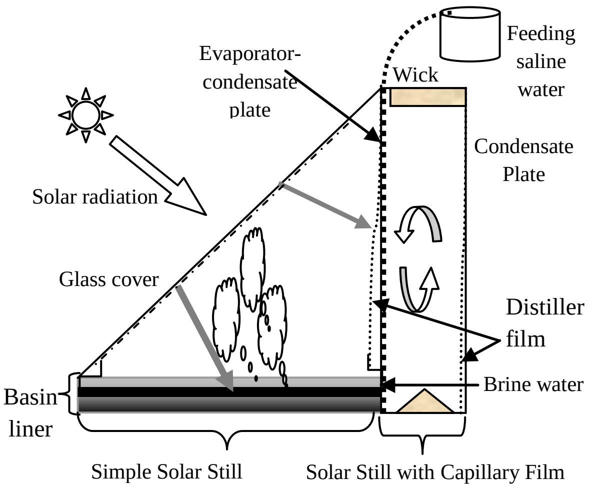

Figure 1: Schematics of a solar still coupled with a SSCF.

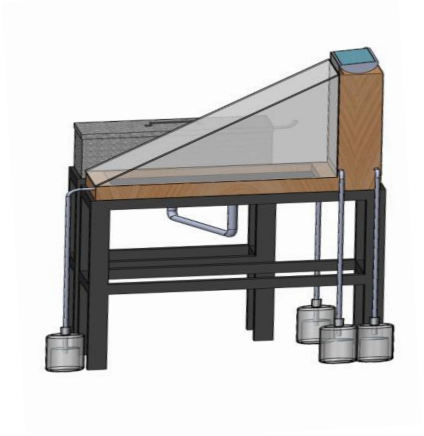

Figure 2: Experimental arrangement

III. MATHEMATICAL MODELING

To establish a model of the distiller, it is necessary to know the various coefficients of heat exchange and mass of the heat-transferring surfaces. Modeling is made on the basis of heat balance and mass on the level of each component of the system. The equations obtained are solved numerically and the results enabled us to determine the various parameters effect on the system performance and thus to estimate the production. With an aim of making the model accessible, we must take into account the following simplifying assumptions [2, 3]:

- The cover thermal inertia is weak; we suppose that the incidental solar rays on the transparent glaze will directly strike the two surfaces of interception; they are the basin and the first vertical plate of the SSCF.
- Temperatures of the exchange walls presumed uniform.
- Condensation surfaces are non wet.
- The distiller cells are thermally well insulated.
- The physical properties of the plates and the pane are considered independent of the temperature and are taken equal to median values.
- Diffused radiation is uniformly of all the directions of the celestial vault.

We can determine the heat balance equations for this device as follows:

- **Balance energy for the glass cover**

$$\frac{\mathrm{dT_v}}{dt}=\left(\frac{1}{\rho_v.e_v.Cp_v}\right).\begin{bmatrix}(h_{cev}+h_{rev}).(T_e+T_v).(S_b/S_v)+fh_e.\dot{M}d_v+\\+h_{rvp}.(T_v-T_p).(S_p/S_v)+\\-h_{cva}.(T_v-T_a)-h_{rva}.(T_v-T_{ciel})+\alpha_v.G\end{bmatrix} \quad (1)$$

- **Balance energy for water in basin**

$$\frac{\mathrm{dT_e}}{dt}=\left(\frac{1}{\rho_e.e_e.Cp_e}\right).\begin{bmatrix}\alpha_e.\tau_v.G+h_{cbe}.(T_b-T_e)+\\-(h_{cev}+h_{rev}).(T_e-T_v).(S_v/S_b)+\\-fh_e.\dot{M}d_v-fh_e.\dot{M}d_p+\\-(h_{cep}+h_{rep}).(T_e-T_p).(S_p/S_b)\end{bmatrix} \quad (2)$$

- **Balance energy for the evaporator**

$$\frac{\mathrm{dT_b}}{dt}=\left(\frac{1}{\rho_b.e_b.Cp_b}\right).\begin{bmatrix}\alpha_b.\tau_v.\tau_e.G-h_{cbe}.(T_b-T_e)+\\-(h_{cba}+h_{rba}+h_{dba}).(T_b-T_a)\end{bmatrix} \quad (3)$$

- **Balance energy for the metal plate**

$$\frac{\mathrm{dT_p}}{dt}=\left(\frac{1}{\rho_p.e_p.Cp_p}\right).\begin{bmatrix}\alpha_p.\tau_v.G+\dot{m}_a.Cp_e.(T_a-T_p)-\dot{m}_s.Cp_e.(T_p-T_a)+\\-fh_p.\dot{M}d_c+(h_{cep}+h_{rep}).(T_e-T_p).(S_b/S_p)+\\-(h_{cpc}+h_{rpc}).(T_p-T_c)+fh_e.\dot{M}d_p\end{bmatrix} \quad (4)$$

- **Balance energy for the condenser plate**

$$\frac{\mathrm{dT_c}}{dt}=\left(\frac{1}{\rho_c.e_c.Cp_c}\right).\begin{bmatrix}(h_{cpc}+h_{rpc}).(T_p-T_c)+fh_p.\dot{M}d_c+\\-h_{cca}.(T_c-T_a)-h_{rca}.(T_c-T_{ciel})\end{bmatrix} \quad (5)$$

The mass balance is simple to write using mass conservation law, since the brackish water flow is the sum of the two flows; distillate mass and brackish water at the outlet:

$$\dot{\mathrm{m}}_{\mathrm{a}}=\dot{M}d_c+\dot{m}_s \quad (6)$$

We defined the coefficients of heat exchange and mass, thus the properties thermo-physical which intervene in the preceding equations as follows.
The radiation exchange between the three surfaces evaluated as continuation:

$$h_{rij}=\sigma.F_{ij}.\left((T_i+273{,}15)^2+(T_j+273{,}15)^2\right).(T_i+T_j+546{,}3)$$

With the form factor evaluated by [10]: that is
$B=\mathrm{h}/le$, $C=lv/le$ So:

$$\mathrm{F_{ij}} = \frac{1}{\pi.B}\left[\begin{array}{l} \frac{1}{4}.\log\left(\left(\frac{(1+B^2).(1+C^2)}{1+B^2+C^2}\right).\left(\frac{B^2.(1+B^2+C^2)}{(1+B^2).(B^2+C^2)}\right)^{B^2} \right. \\ \left. .\left(\frac{C^2.(1+B^2+C^2)}{(1+B^2).(B^2+C^2)}\right)^{C^2}\right) \\ +B.\tan^{-1}\left(\frac{1}{B}\right)+C.\tan^{-1}\left(\frac{1}{C}\right)-\sqrt{B^2+C^2}.\tan^{-1}\left(\frac{1}{B^2+C^2}\right) \end{array}\right]$$

Mass exchange coefficient estimated as follows: $h_m = \left({}^{h_{cij}}\!/_{Cp.\Delta\rho}\right).\left({}^{\nu}\!/_{D_c}\right)^{0,67}$

The parameters that are used in the simulation are given in Table (I, II, III), the thermo-physical properties given in this table are assumed constant in all simulations:

Table I: dry air property

Specific heat	$Cp_{air} = 1008$
Density	$\rho_{air} = 353/(T+273.15)$
Conductivity	$\lambda_{air} = 0.0242 + 7,57.10^{-5}.T$
Dynamic viscosity	$\mu_{air} = (1.7176 + 0.0046.T).10^{-5}$
Thermal diffusivity	$a = (1.8343 + 0.0146.T).10^{-5}$
Prandtl Number	$\Pr = 0,7147 - 2,54.10^{-4}.T$
Thermal expansion	$\beta_{Tair} = 1/(T+273.15)$

Table II: humid air property

Dynamic viscosity	$\mu_h = 1,718.10^{-5} + 4,620.10^{-8}.T$
Thermal expansion	$\beta_{Mh} = 1,6578.10^{-3}.T.\left[0.362.(\frac{P}{P_s})-1\right]^{-1}$
Thermal diffusivity	$D_c = 0,187.10^{-8}.(T+273.15)^{2,072}$
Specific heat	$Cp_h = 999,2 + 0,1434.T + 1,101.10^{-4}.T^2 - 6,7581.10^{-8}T^3$

Table III: brine water property

Density	$\rho_e = 1002,6 - 0,0505.T - 0,00380.T^2$
Conductivity	$\lambda_e = 0,5536 + 2,238.10^{-3}.T - 9,87.10^{-6}.T^2$
Kinematic viscosity	$\nu_e = 17,199.10^{-4} - 0,3389.10^{-4}.T + +0,002.10^{-4}T^2$
Specific heat	$Cp_e = 3958 - 52,3.S + 0,837.T$
Prandtl Number	$\Pr_e = 12,501 - 0,261.T + 1.577.10^{-3}.T^2$

IV. EXPERIMENTATION

The experimental was carried out on the new configuration, which constitutes two different design distillers, traditional distiller with greenhouse effect with only one slope directed towards the south, directly connected with a Solar still with capillary Film (SSCF), at the (LENERZA) laboratory of KASDI MARBAH University, Ouargla (South Algeria). The climatic conditions were favorable (the date 06/08/2007). We chose one well sunny day, clear sky, and absence of strong wind (≤ 5 $m.s^{-1}$).

The cover is out of ordinary glass of 4mm thickness, the basin plate is out of Aluminum 3mm thickness dyed in black matt in order to absorb the maximum of radiations, and of 0,51m × 0,34m dimension. The metal plates, two are out of galvanized steel thickness 0,0006m, the distance between them is equal to 0,03m.

The piece of the used fabric is of nature absorbent porous (gauze of 1mm thickness; this fabric is suitable to form capillary film. The brackish water supply is ensured by the good capillarity of the fabric which acts like a pump. The temperatures of the various components are measured by the thermocouples in type (K) in the middle of each element of the device. The reading of the solar radiation intensity is taken using a solar-meter (Metrasol).

Table captions appear centered above the table in upper and lower case letters. When referring to a table in the text, no abbreviation is used and "Table" is capitalized.

V. RESULTS AND DISCUSSION

5. 1, RESULTS OF MODELING-SIMULATION

The fig 2, Shows the various temperatures evolution (glazing, brackish water, the evaporator, 1st SSCF plate, the condenser), in timing function. The glazing temperature reaches 65°C between solar midday and 14 hours. The brackish water temperatures and the absorber within the basin vary almost in the same way, they are almost superimposed.

On the fig 3, we note that the ambient temperature varies from 25°C to 40°C (August in the south of Algeria), correspondent to the same pace which is obtained in experiments.

The first plate temperatures of SSCF and the condenser plate, reaches 64°C and 50°C respectively. The fig 4 shows that the distillate flow reaches a median value of 2,12 $kg.h^{-1}.m^{-2}$, with a rate of constant feeding about 0,124 $kg.h^{-1}$) correspondent to an average solar flow of 27.96 $MJ.m^{-2}.d^{-1}$. The distillate flow increases according to the brackish water temperature to reach 2,114 $Kg.m^{-2}.d^{-1}$ at 40 °C and of 2,618 $Kg.m^{-2}.d^{-1}$, at 60°C (fig 5). The average conversion rate (is defined as being the link between two flows; distillate and the feeding water) is about 28% in solar midday fig 6. But the total conversion rate does not exceed 13%.

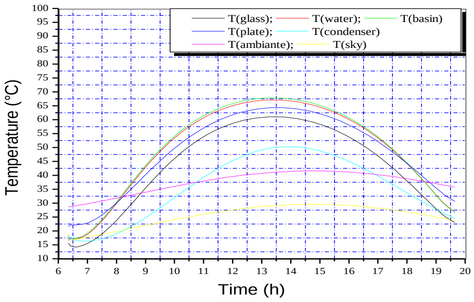

Figure 3: Temperature variation of the device constituents.

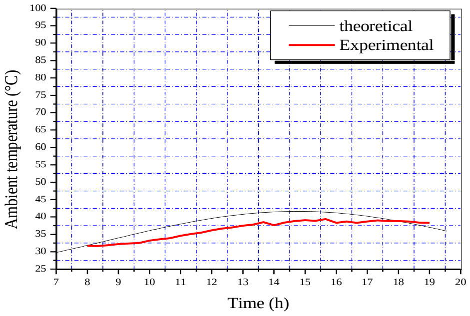

Figure 4: The ambient temperature according to time.

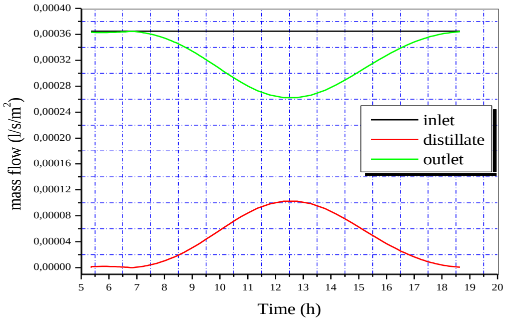

Figure 5: The mass flow evolution; inlet, outlet, distillate.

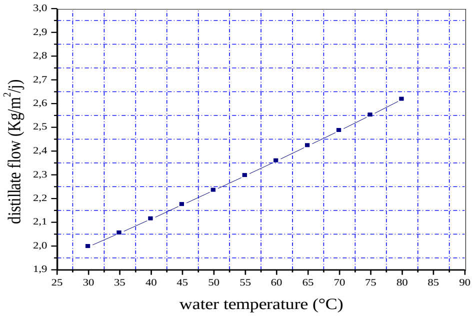

Figure 6: Distillate flow according to the temperature.

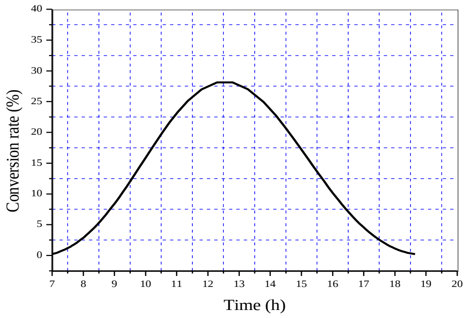

Figure 7: Rate conversion according to time.

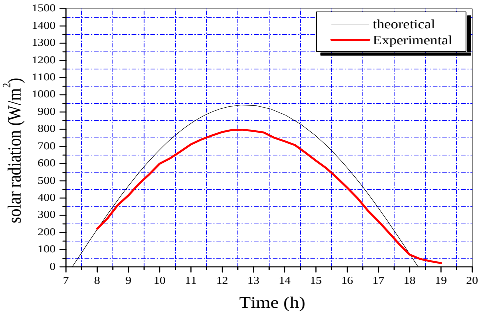

Figure 8: Comparison between radiation flow into theoretical and experimental.

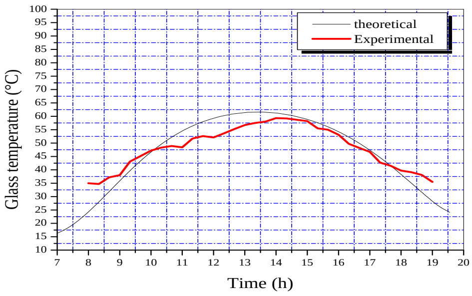

Figure 9-a: The comparison between theory and experiment for the temperature of the glass

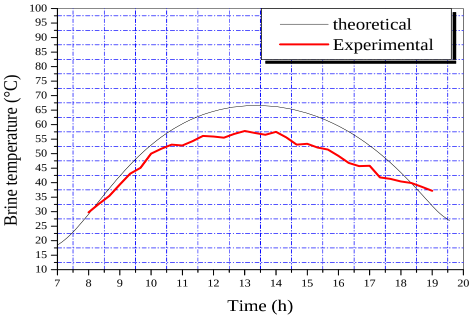

Figure 9-b: The comparison between theory and experiment for the temperature of the brine

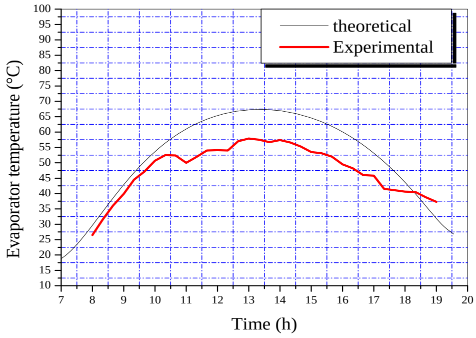

Figure 9-c: The comparison between theory and experiment for the temperature of the evaporator

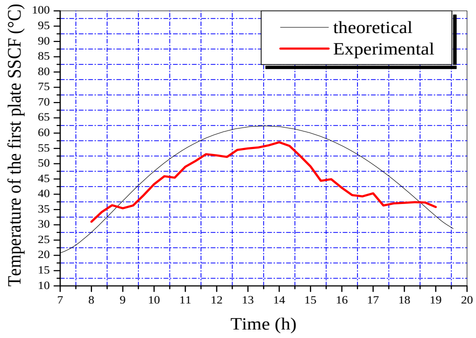

Figure 9-d: The comparison between theory and experiment for the temperature of the first plate SSCF.

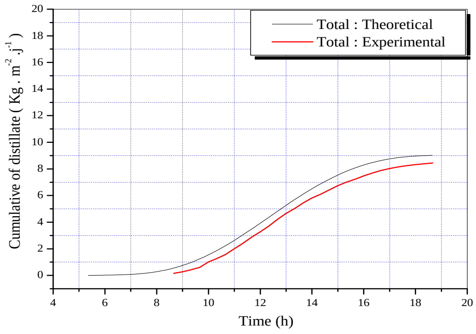

Figure 10: The comparison cumulative of theoretical and experimental productivity.

Table IV: Comparison of the productivity

area of condensation	**Numerical (kg. m^{-2}. J^{-1})**	**Experimental (kg. m^{-2}. J^{-1})**
The glass	4,87	4,53
The metal plate	2,98	1,51
Condenser (SSCF)	2,24	2,05
Overall	9,762	8,43

5. 2, COMPARATIVE STUDY

Fig 7, presents a comparative study between incidental solar radiation given in experiments and the radiation calculated starting from the method worked out by the Kasten [11] formula.

The comparison gives the curves shape of each components temperatures of the device figs (9a, 9b, 9c, 9d), shows a very good correspondence between the two simulation results and experimental, not on the curves only, but also on the quantities of distillates which are obtained has on the condensation walls of multi-effect solar still. Fig 10, we can observe that the daily cumulative resulting from simulation is 9,762kg.m^{-2}.d^{-1} is build to that obtained by the experimental.

VI. CONCLUSION

Our work concerns the theoretical study and the experimentation of the traditional solar distiller coupled with another distiller with capillary film, of reliable capacity and very simple design, the model developed at the point makes it possible to simulate this new configuration functioning. The equations resolution of the heat balances and mass for this new distiller, at a fixed feeding rate, gives the temperatures of the device various components as well as incidental flow and the environment temperature according to time.

The comparison of the experimental results and those of simulation is used to show the coherence of the model. The curves obtained by experimentation and simulation have the same pace. Although the heat absorptive by the SSCF first plate does not come only from received solar energy, but in addition to that of the condensation latent heat on this plate, can re-use this heat to evaporate of another quantity of water which streams on a fabric which is stuck to this plate back face.

Our efforts are directed towards the search of the optimal conditions using this prototype: multiplication of the stages number, and increase in solar flow by the receiving plate slope of the SSCF, and a better dimensioning for the reduction of the thermal losses.

NOMENCLATURES

a	Thermal diffusivity $m^2.s^{-1}$
Cp	Specific heat $J.°C^{-1}.kg^{-1}$
D_c	Air vapor diffusivity $m^2.s^{-1}$
e_i	Thickness m
G	Global irradiation $W.m^{-2}$
h	The vertical plate height m
h	Coefficient of exchange by convection $W.m^{-2}.K^{-1}$
h_m	Exchange Mass coefficient $m^2.s^{-1}$

fh	Evaporation latent heat $J.kg^{-1}$
l_e	The basin length m
l_v	The glass length m
$\dot{m}_a$	Feed rat of saline water $kg.m^{-2}.j^{-1}$
$\dot{m}_s$	Residue Mass rate $kg.m^{-2}.j^{-1}$
$\dot{M}d_i$	Mass rate of distillate $kg.m^{-2}.j^{-1}$
Nu	Number of Nusselt
P	The pressure $N.m^{-2}$
$\Pr$	Number of Prandlt.
T	Temperature K
t	Time s
S	Salinity $g.L^{-1}$
S_i	Surface area m^2

Greek symbols

α	Absorptivity for solar radiation
β	Thermal expansion coefficient of air K^{-1}
λ	Thermal conductivity $W.m^{-1}.K^{-1}$
ν	Kinematic viscosity $m^2.s^{-1}$
μ	dynamic viscosity $N.s.m^{-2}$
ρ	Density, $kg..m^{-3}$
ε	Emissivity
σ	Stefan-Boltzmann constant $W.m^{-2}.K^{-4}$
τ	Transmittance of the cover

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