International Journal of Renewable Energy and Sustainability (RES)
Vol.1pp.14-31

Modelling of temperature for Simple Solar Still hybrid with Heat Pump (SSDHP)

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Abstract—The performance of active solar distiller hybrid with heat pump using different operational parameters is studied theoretically and compared with the experimental data for validation purposes, to find out best factors enhancing still productivity. The thermal performance is evaluated through implementing the following effective parameters; a) with or without orientation, b) with and without heat pump, c) simple or double glass cover , e) temperature differences between the still cover and water. The variation of different parameters with production rate has been studied. It is found that the production rate increases with the increases of water and glass temperature. It can be concluded from this study that active solar stills can be one of the options for enhancing the productivity of stills.

Key words- Modelling temperature, Solar distiller, active solar still

1. INTRODUCTION

Freshwater is a necessity for the maintenance of life and also the key to human's prosperity. Solar desalination is a process of separation of pure water from saline or sea water using solar energy. Comparatively this requires simple technology, eco-friendly, lower maintenance and no energy costs, due to which it can be used anywhere with lesser number of problems.

The solar distillation systems are classified as passive and active solar stills and various scientists throughout the world have carried out research works on design, fabrication methods, testing and performance evaluation, *etc*.

A number of efforts have been made to develop and improve the performance of solar desalination systems, particularly solar stills. The efficiency of the still is directly proportional to the inlet water temperature to still. To increase the temperature of the water inside the still, some researches suggested coupling the still to solar collectors. The results showed an improvement in the still-s performance. One of the main reasons behind the low efficiency of solar stills, which is about 30-40% [1], is the loss latent heat of condensation to the environment and the sensible heat carried away by the condensate. The use of latent heat of condensation to preheat the feed water has shown good improvement in the still-s performance [2,3]. The use of latent heat of condensation of one stage to evaporate water in another stage, as in multi-effect stills, has been studied by many researchers showing very good improvement in the still-s performance [4,5]. Other researchers [6,7] have investigated the concept of evaporation at low temperatures under vacuum conditions and reported good improvement in the system performance. However they used vacuum pumps which require additional energy input to the system.

Pankaj and Agrawal [8] concluded that the black lined solar still operates at higher temperatures as compared to white lined still and since the temperature difference between basin water and glass cover is higher than that of the white lined still, higher distillate output is obtained in the former.

The effect of glass cover thickness increases the productivity which is studied by dr. P. K. shah and Hitesh N. Panchal et al [9] and conclude that lower glass cover thickness distillate output from solar still 4mm glass cover thickness produces more distillate output then 8mm, 12mm. lower glass cover thickness decrease inner glass cover temperature inside solar still and increases temperature difference between water as well as inner glass cover temperature. It also
increase water temperature inside solar still. Hence 4mm thickness of glass cover is suitable for solar still to get maximum productivity.

Tsilingiris [10] have also developed temperature dependent correlations for internal heat transfer coefficients between water and glass cover of solar still and it was shown that these are affected adversely above 60 ºC water temperature. Rubio et al. [11-13] have studied asymmetries in temperatures of water and glass cover, and amount of distillate for a double slope solar still (DSSS) by mathematical model (in terms of lumped parameters, and controlled temperatures of glass cover and basin).

. This research work aims to build a experimental and theoretical model for active solar still to test the thermal performance behaviour under the South Tunisia climate. The active solar still coupled with heat pump with different operational conditions is proposed to improve its productivity. All the results are compared together to reach to the best operating conditions that can be used in future for solar still augmentation for the production of drinking water and industrial use to arid regions in the desert

2. Experimental set up

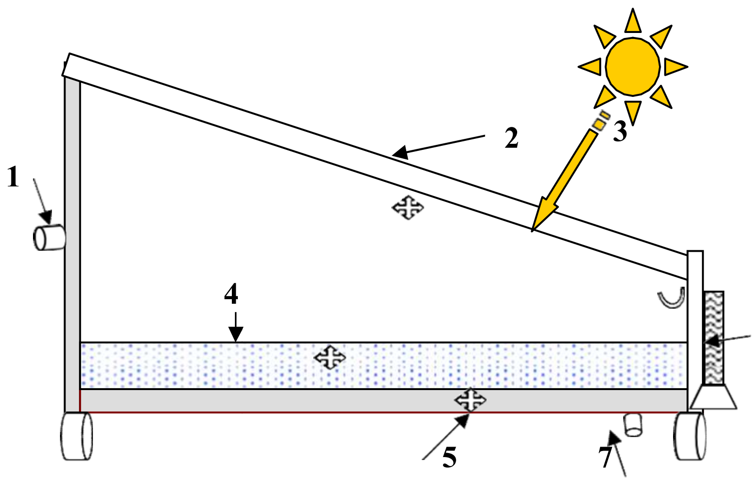
In our experimental work, two models are used. The first one is called the SSS (Simple Solar Still) model, in which the water out put is simply obtained by purely solar energy. This model works only on day. The second one is named the SSDHP (Simple Solar Distiller hybrid with Heat Pump). In this model, heat pump was used in order to increase the quantity of water output. This works by using both purely solar energy and heat pump, consequently it was used on day and night. It should be noticed that, the condenser will contribute to the heating of water and thus its evaporation especially the morning and according to midday to compensate misses it sun. The evaporator will allow while being cooled, a more quantity of condensed water.

The SSD model

Figure1 shows the schematic diagram of the SSD installation. It consists of a basin, which is fabricated from plastic materiel that accommodates the brackish water for a maximum depth of water, which is fixed at 30cm, and is covered by two slopping covers. The height of the lower vertical side of solar still was kept at 60cm and the area of the basin is $0.4m^2$. The operation of the still is very simple: the incident solar radiation is transmitted through the transparent glass cover to the water. As result, the water is evaporated, and reached the glass cover and then collected at the distilled water gutter at condensed phase. Figure 2 shows the photo of SSD.

The SSDHP model

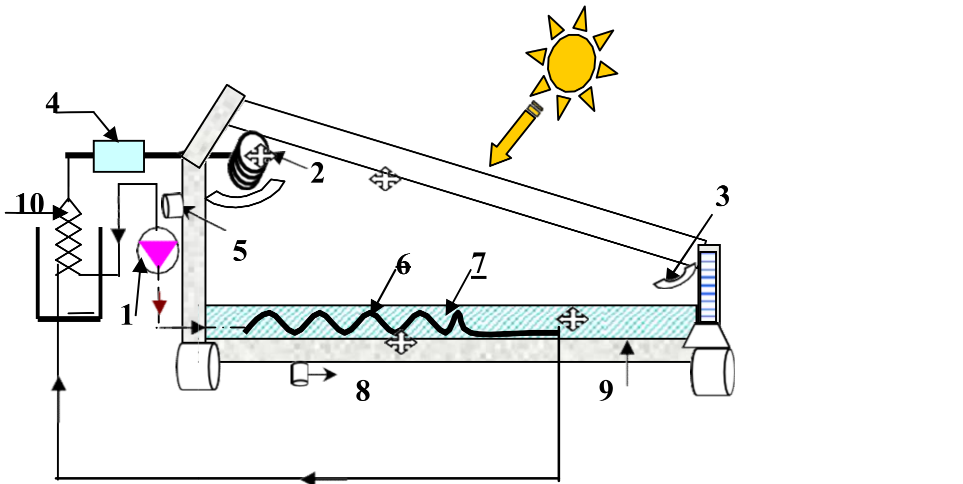
In order to produce more distiller water we added a heat pump to the SSDHP model. Figure 3 shows this model. A condenser is immersed in basin water to increase temperature of water and then evaporated quantity of water will increase. The condenser located near the upper region of the glass cover enhances



1- Inner water, 2-Glass cover , 3-Sun , 4- Saline water , 5- Basin, 6-Distiller water , 7- Outer water, Position thermometers

Fig 2.1. Schematics of a Simple Solar Distiller SSD

Fig 2.2. Photo of Simple Solar Distiller SSD



1- Compressor, 2-Evaporator, 3- Water distiller , 4- Detendeur, 5-Inner saline water , 6- Condenser, 7- Saline water, 8- outer saline water , 9-Insolation , 10-regulation system .   Position thermometers

Fig .2.3. Schematics of a Simple Solar Distiller hybrid with Heat Pump SSDHP

Fig 2.4 Photo of SSDHP

The condensation of the water vapor, and the refrigerant (R12), leaving the condenser is then introduced in a heat exchanger filled with fresh water in order to maintain the temperature of the refrigerant. Then the refrigerant enters the evaporator at low pressure inducing the condensation of water vapor. As a consequence, a more amount of condensed water will be recuperated at the distilled water gutter. The process is done naturally. Figure 4 shows the photo of SSDHP

2.3.Experimental parameters

For the installation, we assigned the value (0) for which the SSD and the SSDHP plants are orientation towards the south, the value (1) periodically directional towards the sun. Table 1 shown this resultats

Table 1: Study for differences configurations

Position	Vitrage	PAC
0	0	0
0	0	1
1	1	0
1	1	1

For the glass cover, the value (0) is given when a single glass cover is used and the value (1) is given when we used double glass cover. Similarly, the value (0) is given in absence of heat pump, and the value (1) is given when the heat pump is used.

3. Theoretical analysis of active solar distillation system

The thermal models of the simple solar distiller hybrid with heat pump are developed based on the energy balance equations. The following assumptions have been considered for writing the energy balance equation in terms of w/m^2

- Heat flow through a cover is one dimensional

- heat losses is neglected
- The heat losses of the insulation is neglected
- The heat for extraction distiller is neglected
- No stratification of water occurs in the basin of the solar still.
- Speed of wind is constant

In solar distillation systems, the heat transfer can be classified in terms of external and internal heat transfer. The external heat transfer are mainly governed by conduction, convection and radiation processes, which are independent of each other, these are, the heat of the glass cover and the bottom and sides insulation. Heat transfer within the solar still is referred to as internal heat transfer who mainly consists of radiation, convection and Evaporation.
External heat transfer covers exchanges between the outside of the solar still and the surrounding for example heat transfer from the glass to the ambient, and the heat transfer from water that exist in the basin to the ambient. The theoretical model analysis can be made by dividing the heat transfer process that occurs on the still into two types, External and Internal heat transfer [14, 15].

Heat transfer in active solar still
The details of various heat transfers that take place in active solar still are shown in Figure 3.1

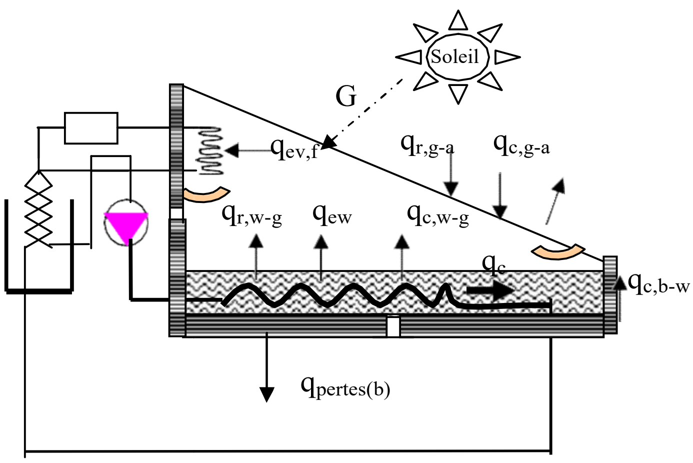


Fig. 3.1. Energy balance of a SSDHP

- The solar flow (G), striking the surface of the absorbed and the surface absorbent (absorber evaporator
- The glass gives in ambient, the heat flux $q_{r,g-a}$ by radiative heat and $q_{c,g-a}$ by convection and by conduction q_{cd}
- The glass receives from evaporator the heat flux q_{ew}
- The evaporator exchanges with the condenser the heat flux $q_{r,w-g}$ by radiative heat and q_{cw-e} by convetion

- The condenser gives to ambient the heat flux $q_{c,b-w}$ by convection and q_{losses}

4.2 Energy balance in the glass cover

The energy balance equation for the glass cover can be written as:

$$m_g C_{pg} \frac{dT_g}{dt} = \alpha_g (1-\varphi_g) G + (q_{ew} + q_{r,w-g} + q_{c,w-g}) - q_{r,g-a} - q_{c,g-a} \quad (4.1)$$

Where

$$\frac{dT_g}{dt} = \frac{1}{(m_g C_{pg})} [\alpha_g (1-\varphi_g) G + (q_{ew} + q_{r,w-g} + q_{c,w-g}) - q_{r,g-a} - q_{c,g-a}] \quad (4.2)$$

Energy balance in the evaporator

The energy balance for the evaporator is :

$$\frac{m_e c_{pe}}{S_e} \frac{dT_e}{dt} = [q_{c,w-e} + q_{ew,w-e} - q_{ev,f}] \quad (4.3)$$

Where

$$\frac{dT_e}{dt} = \frac{S_e}{(m_e C_{pe})} [q_{c,w-e} + q_{ew,w-e} - q_{ev,f}] \quad (4.4)$$

Energy balance in water

The energy balance in water is

$$\frac{dT_w}{dt} = \frac{S_w}{(m_w C_{pw})} [(1-\alpha_g)(1-\varphi_g)(1-\alpha_w)\alpha_w G + q_{c,b-w} - q_{r,w-g} - q_{ew,w-e} + q_c] \quad (4.5)$$

q_c : heat flux in the compressor

The expression of heat flux and the heat coefficient are :

$$q_{r,w-g} = 0.9\sigma (T_w^4 - T_g^4) \quad (4.6)$$

$$q_{c,w-g} = h_{c,w-g} (T_w - T_g) \quad (4.7)$$

$$q_{c,b-w} = h_{c,b-w} (T_b - T_w) \quad (4.8)$$

$$q_{c,w-e} = h_{c,w-e} (T_w - T_e) \quad (4.9)$$

$$q_{ew,w-e} = h_{ew,w-e} (T_w - T_e) \quad (4.10)$$

The heat flux in the evaporator is given by [16]

$$q_{ev,f} = h_{ev,f} (T_e - T_f) \quad (4.11)$$

The coefficient of evaporator transfer in the refrigerant is [16] :

$$h_{ev,f} = \frac{Nu.k}{L} \quad (4.12)$$

The heat flux of water q_c is :

$$q_c = \frac{COP.W}{S} \quad (4.13)$$

Where the performance coefficient is calculated by [17]

$$COP = \frac{T_w}{T_w - T_g} \quad (4.14)$$

The coefficient of transfer between water and the basin is given by the expression [16] :

$$\begin{cases} h_{c,b-w} = 0.54 \dfrac{k_w Ra^{1/3}}{L} pour 10^4 \le Ra \le 10^7 \\ h_{c,b-w} = 0.15 \dfrac{k_w Ra^{1/3}}{L} pour 10^7 \le Ra \le 10^{11} \end{cases} \quad (4.15)$$

Energy balance in water

The energy balance in the basin :

$$\frac{m_b C_{pb}}{S_B} \frac{dT_b}{dt} = (1-\alpha_g)(1-\varphi_g)(1-\alpha_w)\alpha_b G - q_{c,b-w} - q_{petes(b)} \quad (4.16)$$

Where:

$$\frac{dT_b}{dt} = \frac{S_b}{(m_b C_{pb})}[(1-\alpha_g)(1-\varphi_g)(1-\alpha_w)\alpha_b G - q_{c,b-w} - q_{perte(b)}] \quad (4.17)$$

4.6 Energy balance in yield :

The distiller yields are given bay this equation:

$$\dot{m}_e = \frac{dm_e}{dt} = \frac{h_{ew}(T_w - T_g)}{L_v} \quad (4.18)$$

5. Solution of the systems equations:

The functions of simple solar distiller coupled with heat pump are resolved by differential equations of first order

$$\begin{cases} \dfrac{dT_g}{dt} = \dfrac{1}{(m_g C_{pg})}[\alpha_g(1-\varphi_g)G + (q_{ew} + q_{r,w-g} + q_{c,w-g}) - q_{r,g-a} - q_{c,g-a}] \\ \dfrac{dT_w}{dt} = \dfrac{1}{(m_w C_{pw})}[(1-\alpha_g)(1-\varphi_g)(1-\alpha_w)\alpha_w G + q_{c,b-w} - q_{r,w-g} - q_{ew,w-e}] \\ \dfrac{dT_b}{dt} = \dfrac{1}{(m_b C_{pb})}[(1-\alpha_g)(1-\varphi_g)(1-\alpha_w)\alpha_b G - q_{c,b-w} - q_{perte(b)}] \\ \dfrac{dT_e}{dt} = \dfrac{1}{(m_e C_{pe})}[q_{cw-e} + q_{ew,w-e} - q_{ev,f}] \\ \dot{m}_e = \dfrac{dm_e}{dt} = \dfrac{h_{ew}(T_w - T_g)}{L_v} \end{cases} \quad (4.19)$$

In order to determined the temperatures of basin T_b, water T_w, in the glass T_g and in the evaporator T_e finally the yield of water distiller m_e systems of equations are solved by Runge Kutta method.

$$\frac{dT_i}{dt} = f(T_w, T_g, T_e \ldots t)$$

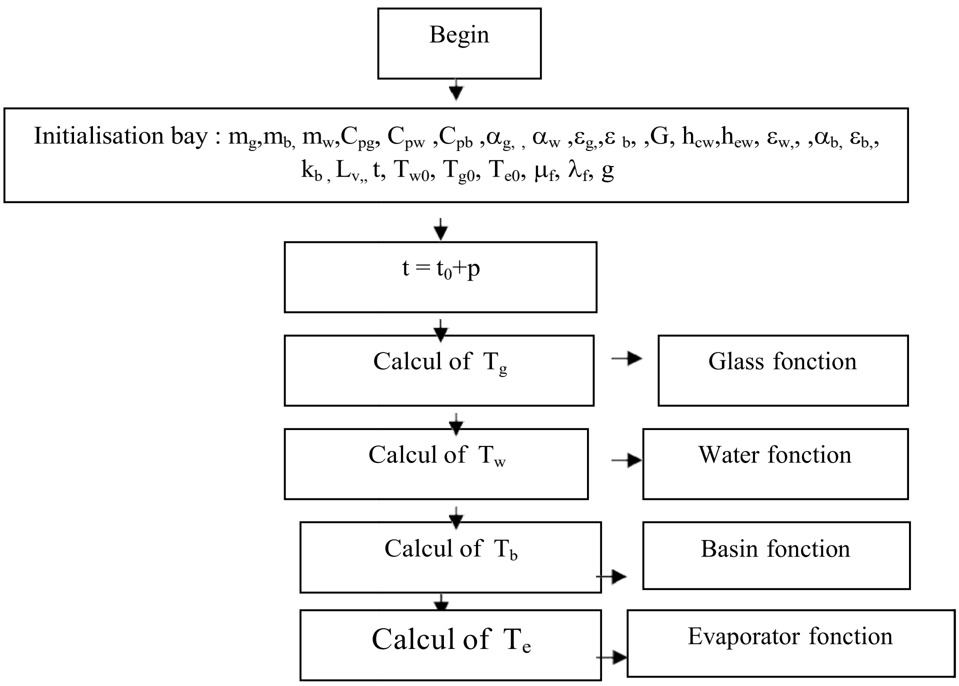
Where i=1 to 5

t : represented the time where $t = t_0 + p$

t_0 = the sun level time and p is the pas.

- **Organigramme de calcul**

This systems of equations are calculated by Matlab logiciel. L'organigramme is represented in Figure 6.1



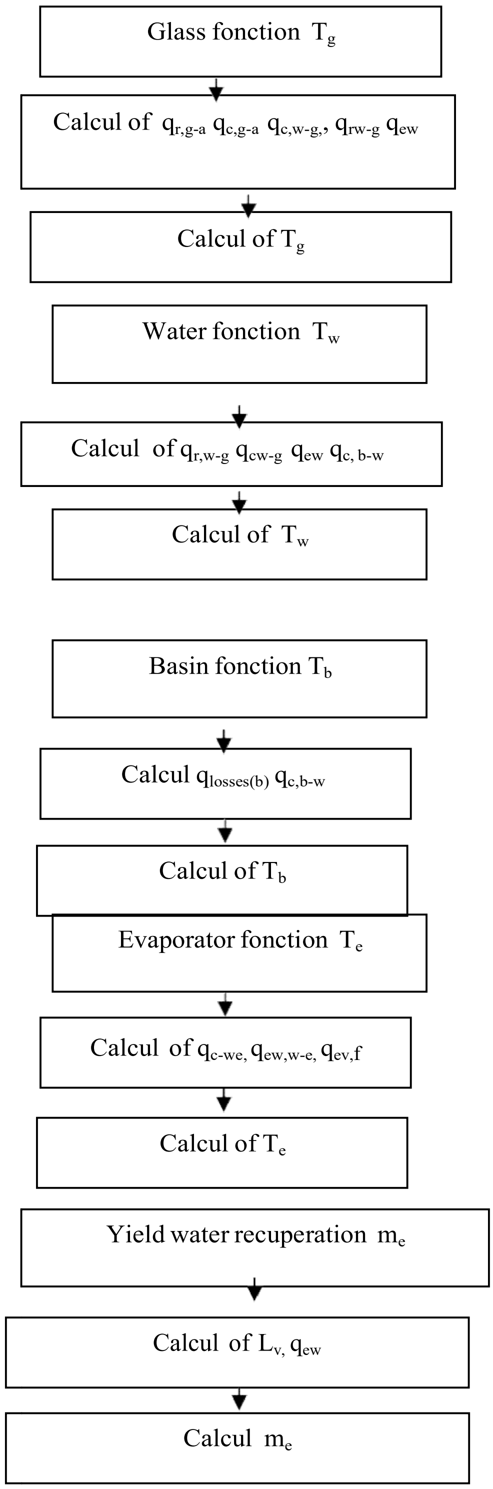


Fig 6.1 Organigramme of calcul for differents parameters

6. Experimental results :

Figure represent the measured and the theoretical solar intensities. From Figure 6.1 it can be noticed that the solar intensity increases until it reaches the maximum in the solar day 900 Wm^{-2}, then it decreases with time after this maximum value in the after noon. Also from figure 6.1, we can highlight the importance of solar intensity on the productivity, when the solar intensity increases, the productivity should increase. The Figure shows also that the concordance enters the experimental and calculated global illumination is acceptable. Therefore, we predicate that the solar still efficiency would be close to the same value [18]

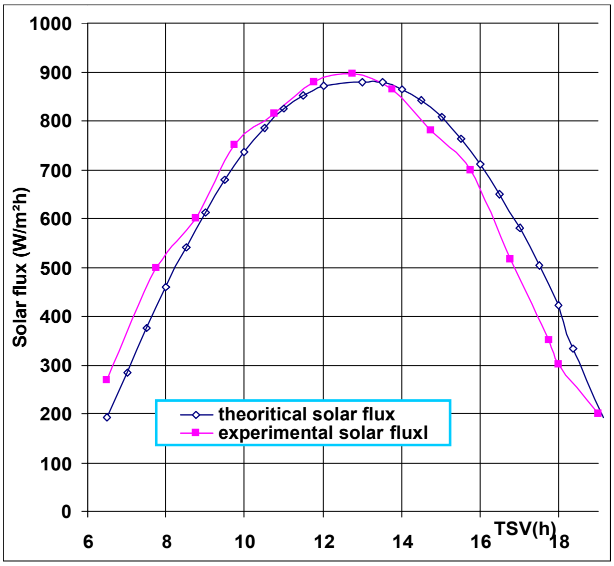


Fig 6.1 : Simulation of solar flux

7. Temperature simulation

Figure7.1 shows the simulation results of the hourly variation of the saline water temperature T_w, glass cove T_g, and the basin temperature T_b during one day of solar still testing. As shown, the temperature of saline water, glass cover and the basin increases in the morning hours to reach maximum value around midday before it start to reduce late in the afternoon. It can be noted that the glass cover attains the maximum temperature faster than saline water and the basin . This is in fact because the saline water has higher thermal heat capacity than that of glass cover.

The resolution of the differentiel system can be determine the temperature in various position of the ditillers for the studied configuration. The results profils of the simlations are schown on figures 7.1 and 7.2 the configurations (000 and 100) exposed that the temeratures follow a parabolic profile similar to that of the experiment and have the similar flow of the solar is the shape of a bell[19]

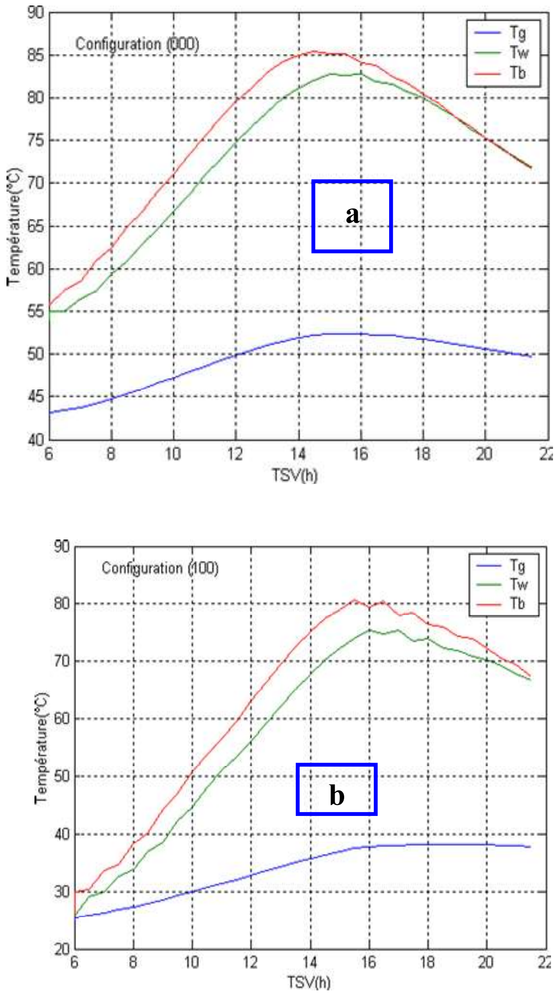
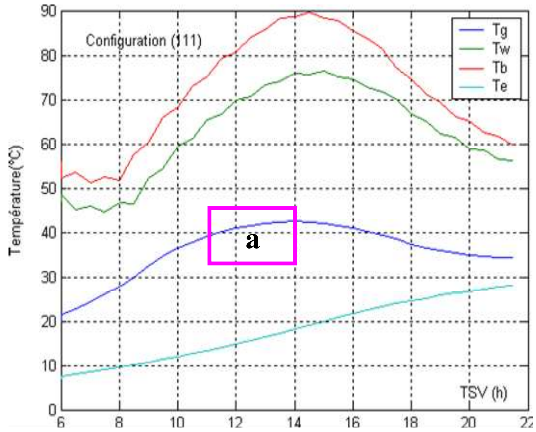


Fig.7.1 (a, b) . Variation des différentes températures théoriques pour les configurations (000) et (100) en fonction du temps.



For the PAC configuration we added the temperature of the evaporator. The evolutions of the temperatures follow the same for the configurations with PAC (111 and 001) is shown on the Figure (7.2). Is observed in the various configurations which the temperatures (Te) at the level of the evaporator takes an increasing speed. This is to explain by that the effect of the evaporator imports the effect of the solar flow at the end of the day

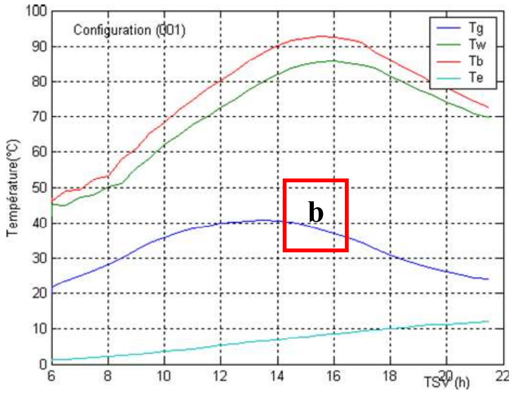


Fig7.2 (a, b) : Variation des différentes températures théoriques pour la configuration (111) et (001) en fonction du temps

The production of the distiller increases according to the plan until a maximal value at about 14 TSV (Figures 8 .1 and 8.2) , then it decreases according to the time, because indeed, the intensity of the solar flow evolves in the same way and it is maximal at about 13 TSV. The production is raised all the more as the received irradiation is more important.The increase of the production growth by the temperature of the water, the absorber and the decrease of the outside temperature of the glass and the condenser.

The yields of the distillate water is in order of 0.35 Lm-2h-1 it was obtained for the configurations without heat pump (Figure 8.2) [20]. This flow reaches 1.7 Lm-2h-1 values at noon solar energy true for the configuration with heat pump (Figure 8.1). The indeed of addition heat pump increases on one hand the evaporation at the level of the basin under the influence of the heat to evacuate by the condenser and on the other hand the evaporator helps in the condensation of the vapour[21]

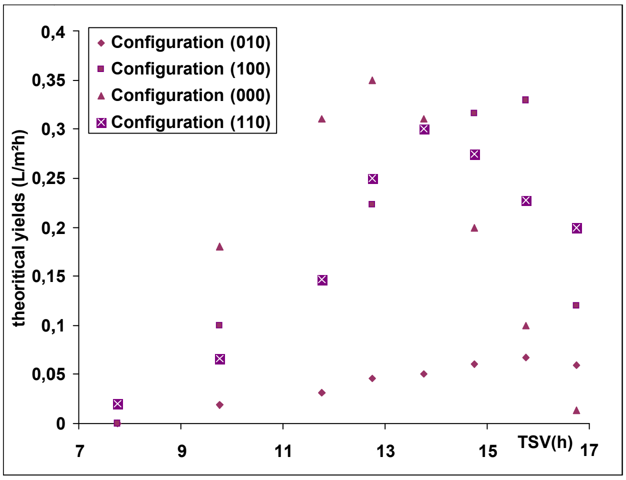


Fig 8 .1. Theoretical yields for different configurations for SSD model

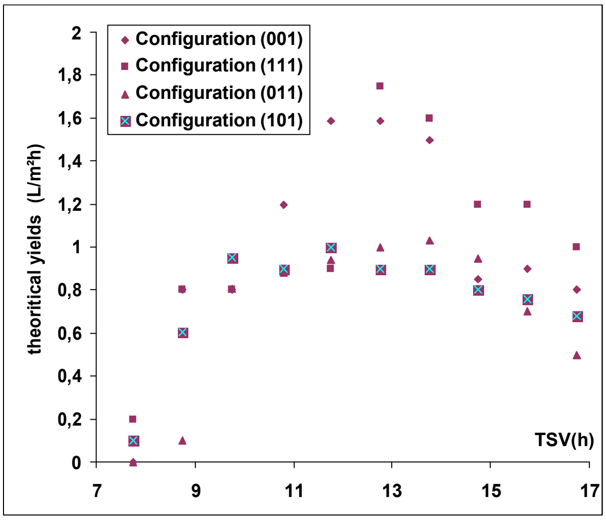
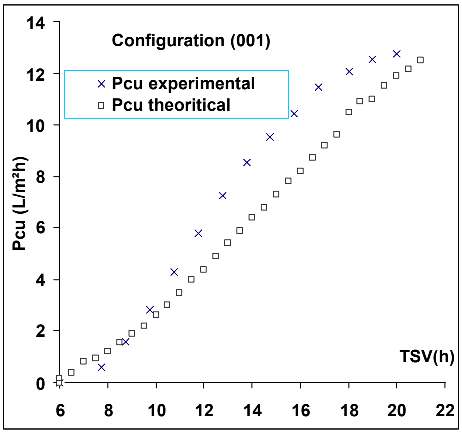


Fig 8.2. Theoretical yields for different configurations for SSDHP model

The comparison of the accumulated experimental and theoretical productivity Pcu (Figure1) according to time for the studied configurations. We noticed that for both cases they have the same speeds with a more clear hop between 10 TSV and 16 TSV. Indeed the affected results agree well with those experimental until 14 TSV for all the configurations with and without CAP. A considerable opening is observed for the configurations (000 and 001). This difference can be explained by the variation of the wind speed which is supposed constant during our work [22].



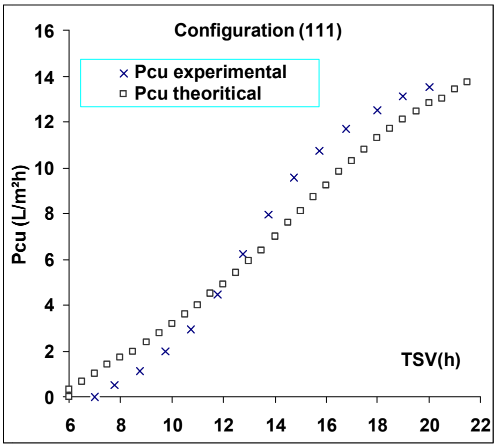


Figure 8.5 : Variation de la productivité cumulée (Pcu) e fonction du temps. Configurations (001) et (111)

Conclusion

In this study, the modelling of a solar distiller coupled to a heat pump was made. The model is based on equations reacting heat and mass transfer in the distiller. The performances of the distiller were carried out by comparison with the performance of a conventional solar distiller. Indeed, the productivity of our distiller is 75% higher than the productivity of a conventional solar distiller. The influence of some parameters involved in the operation of the distiller was presented. The simulation results are in good agreement with the experimental results.

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Nomenclature

A : Area, m2
C : Specific heat, J.kg-1.K-1
COP : Coefficient of performance
h : Convection heat transfer coefficient, W.m-2.K-1
k : Thermal conductivity.m-1.K-1
L : Specific length, m
H : Specific latent heat of vaporization J.kg-1
m : Specific mass, kg.m-2
P : Pressure, N.m-2
q : Heat flux, W.m-2
Ra : Rayleigh number
T : Temperature, T
U : Overall heat transfer coefficient, W.m-2.K-1
V : Velocity, m.s-1
W : Compressor power, W

Nomenclature

α : Absorptivity

ε : Emissivity
ρ : Reflectivity
σ : Stefan-Boltzmann constant
a : Ambient
b : Basin
c : Convection, condensate
e : Evaporator
ev : Evaporation
f:: Refrigerant
g : Glass
H : Horizontal
i : Insulation
r : Radiative
w : Water

ANNEXE

$$q_{c,w-g} = 0.884\left[\left(T_w - T_g\right) + \left(\frac{\left(P_w - P_g\right)\left(273 + T_w\right)}{268.9.10^3 - P_w}\right)\right]^{1/3}(T_w - T_g) = h_{cw}(T_w - T_g)$$

$$h_{cw} = 0.884\left[\left(T_w - T_g\right) + \left(\frac{\left(P_w - P_g\right)\left(273 + T_w\right)}{268.9.10^3 - P_w}\right)\right]^{1/3}$$

$$q_{ew} = 16.273.10^{-3}\, h_{cw}(P_w - P_g)$$

$$h_{ew} = 16.273.10^{-3}\, h_{cw}\frac{(P_w - P_g)}{(T_w - T_g)}$$

$$P_w = exp\left(25.317 - \left(\frac{5144}{237 + T_w}\right)\right)$$

$$P_g = exp\left(25.317 - \left(\frac{5144}{237 + T_g}\right)\right)$$

$$\mathrm{q_{r,g-a} = h_{r,g-ciel}(T_g - T_{ciel})}$$

$$\mathrm{T_{ciel} = T_a - 12}$$

$$h_{r,g-ciel} = \frac{\varepsilon_g \sigma[(T_g)^4 - (T_{ciel})^4]}{(T_g - T_{ciel})}$$

$$q_{c,g-a} = h_{c,g\text{-}a}\,(T_g - T_a)$$

$$h_{c,g-a} = 5.7 + 3.8\ V$$

$$q_{perte(b)} = U_b\,(T_b - T_a)$$

$$U_b = \frac{\lambda_b}{e_b}$$