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Mathematical Analysis of a New Design for Cascade Solar Still

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Abstract Fresh water available on earth is very scared. Yet the demand of fresh water is incessantly increasing, due to population growth and rapid industrialization. According to the United Nations, in 2025, 63% of the world's population will be living in scarce water areas. The provision of freshwater is becoming a gradually more important issue in many areas of the world. Oceans are the only available source for large amount of water. Ocean water presents high salinity, so there is a need to desalinate ocean water for everyday consumption. Solar stills are widely used in solar desalination for being very simple devices, easy to fabricate and require only few maintenance. In this paper, a new approach to design a solar still absorber plate was developed and the effect of this design on the productivity was investigated theoretically. A mathematical model was developed to calculate the theoretical productivity of the solar still. The energy balance equations for the various elements of the solar still are formulated and numerically solved using the dynamic simulation program Matlab/Simulink™. The performance of the still was investigated. The results show that the thermal performance of a modified stepped solar still can be considerably improved through new introduced modifications.

Keywords: Desalination, brackish water, stepped solar still, cascade solar still, wick type stills.

1 Introduction

Water forms 70% of the human body, and is considered as one of the prime elements responsible for life on earth. It covers three-fourths of the surface of the earth (approximately 75%). However 97% of this water is salty, 2% of the water on earth is glacier ice at the North and South Poles and less than 1% of all the water on earth is fresh water that can actually be used for living beings on earth daily needs.

Water resources in Morocco are limited and unevenly distributed. The annual average precipitation in Morocco is 150 billion m^3, varying year by year between 50 billion m^3 and 400 billion m^3. Annual evaporation is, on average, 121 billion m^3. Of the remaining 29 billion m^3, about 22 billion m^3 of water are technically and economically exploitable. These exploitable resources are comprised between 18 billion m^3 of surface water and 4 billion m^3 of groundwater [Choukr-Allah, (2011)].

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Solar desalination is a good process for distilling saline/brackish water by using solar energy for two reasons: Firstly Morocco has an important solar energy potential. The annual days of sunshine value, the annual mean direct normal and global irradiation can reach respectively 3405 hours, 7.22 kwh/m^2 and 5.86 kwh/m^2 [Nfaoui and Sayigh, (2015)]. Secondly, in comparison with other forms of energy sources, solar energy is clean and can be supplied without any environmental pollution.

Solar desalination systems are mainly classified into two systems:

- Direct solar desalination
- Indirect solar desalination

In direct desalination, solar energy is directly applied to solar collectors to get the distillate.

Solar stills are widely used in solar desalination as they are very simple devices, easy to fabricate and require less maintenance than many other devices. However in comparison with other conventional desalination methods, the yield of the single basin solar still is very low.

The various factors affecting the productivity of solar still are solar intensity, wind velocity, ambient temperature, water–glass temperature difference, free surface area of water, absorber plate area, temperature of inlet water, glass angle and depth of water. Solar intensity, wind velocity and ambient temperature cannot be controlled as they are metrological parameters. Yet, the remaining parameters can be varied to enhance the productivity of the solar stills.

1.1 Conventional solar still process

Desalination is processed in a conventional solar still in 3 steps:

(1) Received solar radiation is effectively absorbed by a black surface and heat is transferred to the water in the basin.

(2) The increase of water temperature causes evaporation.

(3) A sloping transparent glass cover is provided at the top. Water vapor produced by evaporation raises upward and condenses on the inner surface of the glass cover which is relatively cold.

In order to enhance the performance of conventional solar stills, several designs were carried out. Among recent works, [Murugavel, Srithar (2011)] used a double slope solar still with different wick materials and minimum mass of water.

The depth of water in the solar still inversely affects its productivity. Investigations indicated that a reduction of the brine depth in the still improves the productivity, mainly due to the higher basin temperature. Maintaining the minimum depth in the solar still is very difficult. Therefore for maintaining minimum depth, a plastic solar water purifier was designed, made and tested successfully by [Ward (2003)], it consists of a black plastic sheet which was vacuum formed onto an aluminum pattern. Also a stepped solar still was used by [Velmuruga, Pandiarajan, Guruparan, Subramanian, Prabaharan, Srithar (2009)].

[Dashtban and Tabrizi (2011)] integrated PCM storage to a weir-type cascade solar still in the view of keeping the operating temperature of the still high enough to produce distillated water during the lack of sunshine.

Recently, inclined solar stills have received much attention due to higher productivity than the basin types. This kind of solar still offers minimum depth of water, better water orientation with respect to the transparent cover and, hence, a minimum air gap between them.

1.2 Stepped solar still process

The stepped still has the same construction of conventional still; in addition, the absorber plate is made of number of steps. The absorber plate temperature and basin water temperature of stepped solar still are higher than those of conventional still. This may be referred to two reasons:

(1) A smaller air volume is trapped inside the still chamber than in the conventional still and therefore heating up the trapped air will be much faster

(2) The step-wise basin provides higher heat and mass transfer surface area than the flat basin [Abdallah, Badran and Abu-Khader, (2006)]

This consequently leads to increase the basin water temperature of stepped solar still.

1.3 Techniques used to improve the performance of the stepped solar still

[Velmurugan, SenthilKumaran, NiranjanPrabhu, Srithar (2008)] designed and analyzed a stepped still with two different depth of trays (10mm and 5 mm). To improve the productivity, experiments were carried out by integrating small fins in basin plate and adding sponges in the trays.

[Kabeel, Khalil, Omara, Younes (2012)] studied theoretically and experimentally the effect of varying depth and width of trays on the performance of the stepped still. The productivity of modified still is about 57.3% higher than that of the conventional still.

The effect of shape of the absorber surface of the stepped solar still on the distillate yield was studied by [Jagannath and Lalit (2013)]. The average daily water production has been found to be 56.60% for the convex absorber plate surface and 29.24% for the concave absorber plate surface higher than that of flat type stepped solar still, respectively.

[Omara, Kabeel and Younes (2013)] investigated a stepped solar still with tray and internal reflectors on the vertical sides of the steps. The productivity of modified device with reflectors is higher than that of conventional still by 75%. [Omara, Kabeel and Younes (2014)] fabricated and studied the performance of a modified stepped solar still with internal and external (top and bottom) reflectors. The results indicated that, the productivity of the modified system is higher than that for conventional still approximately by 125%.

The main objective of the present work is to investigate and enhance the performance of a stepped solar still. A new design of a cascade solar still with sloped absorber plate and weirs was considered, based on the optimum annual inclination for the city of Rabat in

Morocco with view of enhancing the hourly productivity. The design was based on the development of a mathematical model that served to compare expected results of the new design to conventional stepped solar stills.

The energy balance equations for the various elements of the still as well as for the new absorber plate are formulated and numerically solved.

The model results of the solar still are validated with experimental data of [Montazeri, Banakar and Ghobadian (2013)]. Moreover a comparison between modified stepped solar still and ordinary design were carried out to evaluate the developed desalination system performance under the same climate conditions and with the same physical properties.

2 System description

As shown in Fig. 1, the classical ordinary form of cascade solar still has plate absorber with horizontal and vertical surfaces; the angle between the two surfaces is about 90°. In the new design the glass cover and the vertical surface of absorber plate are inclined with angles of 25° and 35° respectively for better orientation relative to the sun. The Absorber plate inclination was equal to the latitude of Rabat (34°47'N). So our pattern as shown in Fig. 2 consists of horizontal and vertical/inclined types of absorber plates and the angle between the two surfaces was about 145°.

In order to improve the performance of cascade solar still, the water transit time on the absorber plate should be maximized. Therefore in the new design of slope absorber plate we added different weirs to the surface of absorption.

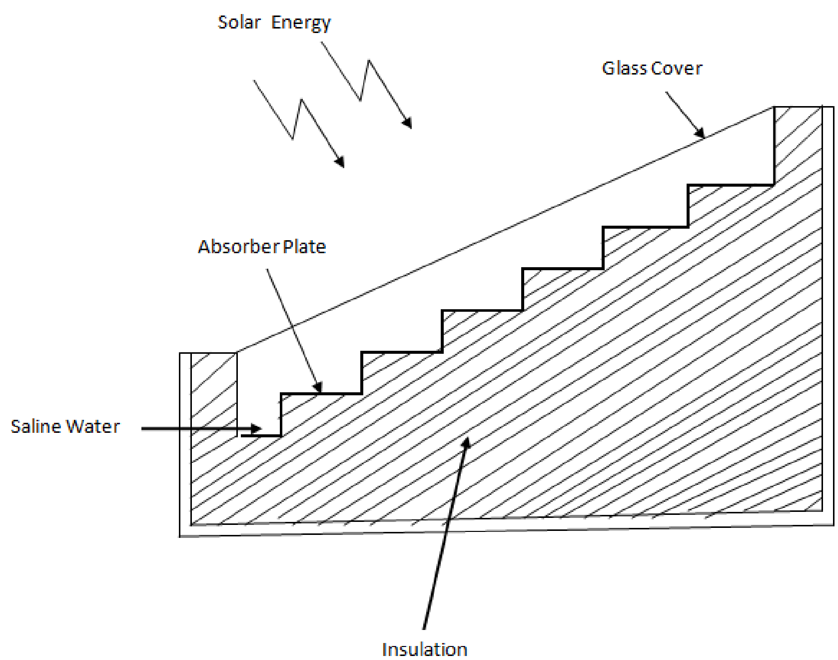


Figure 1: Stepped solar still.

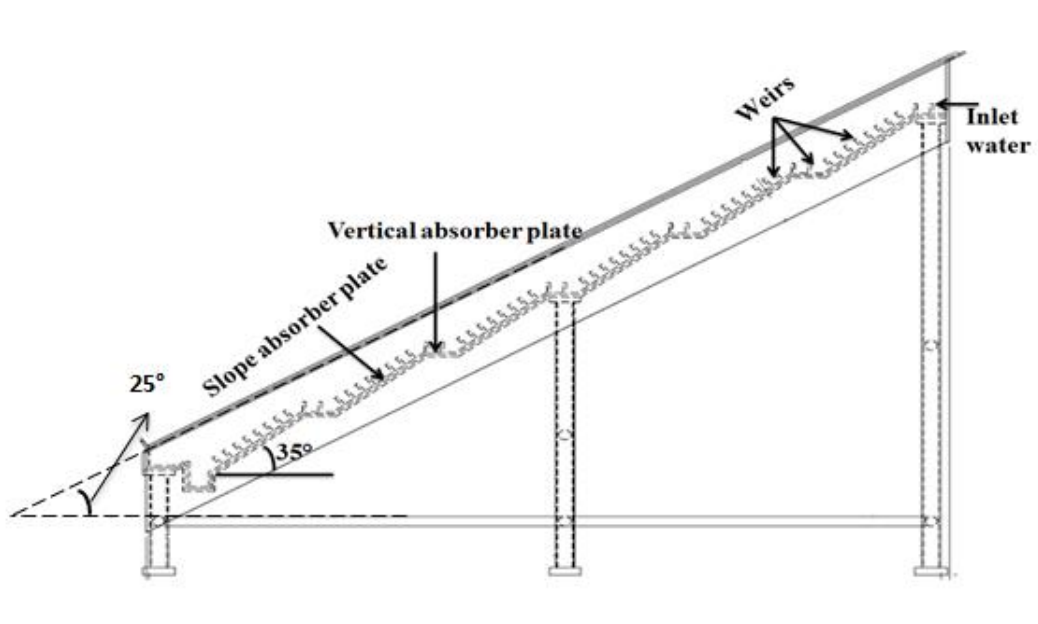


Figure 2: New design of stepped absorber plate(with slope surface and weirs)

2.1 Solar still construction

Fig. 3 shows the different elements of our pattern.

- *Glass cover technology*

The solar still has a top cover made of glass. The glass cover has two functions:

First, solar radiation passes through the glass cover which prevents the radiation to be-transmitted by the inner face of the basin with a low temperature. Second, the glass cover presents a condensing surface of the steam, for this purpose, a good wettability is necessary.

We used inclined glass cover (more than 25 °) for two reasons:

- *To provide better orientation relative to the incident radiation*
- *To facilitate the runoff of condensed water to the collector*

>Basin technology

The basin is made of metal (aluminum); thermal insulation is achieved by a coating inside the basin. The basin bottom sealing is achieved by a synthetic rubber covering mat.

The absorber plate is made of aluminum and painted black. It consists of horizontal and sloped surfaces with black metal baffle on the inner face.

The new construction of the absorber plate presents the following advantages:

- *Better absorption of solar radiation*
- *Minimum depth of water*
- *Quick water Heating*

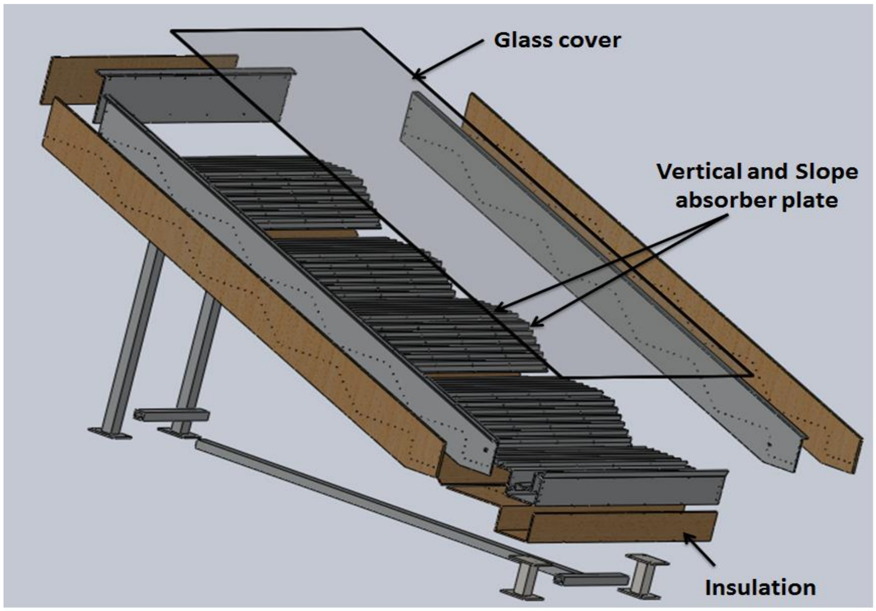


Figure 3: Different elements of new design for cascade solar still

3 Mathematical and thermal analysis

To evaluate the temperature of the condensing glass cover, brackish water and absorber plate, the energy balance equations are written under the following hypotheses:

- Heat losses from the sides of the solar still are negligible
- There is no air leakage from the still
- The cover is clean
- The temperature of each component is uniform
- At the beginning of the experiment, the temperatures of all surfaces are equal to the ambient temperature
- The condensation takes place only on the cover.
- The glass has good moisture
- The concentration of the brine is not involved in the heat and mass transfer.
- The basin is waterproof

The analytical results are obtained by solving the energy balance equations for the absorber plate, saline water and glass cover of the solar still, using Runge-Kutta-Fehlberg 45 (ODE45) which is the basis process for the dynamic simulation program Matlab/Simulink™. The method is 4th order accurate. The saline water temperature, basin plate temperature and glass cover temperature can be evaluated at every instant.

In the subsequent equations, Tg, Tw and Tb are average glass cover temperature, water temperature and absorber plate temperature, respectively, all expressed in ℃.

3.1 Various thermal energy balance of solar still

3.1.1 Thermal energy balance of the condensing glass cover

For the glass cover, the thermal energy balance is expressed by:

$$C_{pg}m_g\frac{dT_g}{dt} = Q_{rwg} + Q_{cwg} + Q_{ewg} - Q_{rgsky} - Q_{cga} + P_g \quad (1)$$

The radiative heat flux density between the glass cover and the sky is expressed as follows:

$$Q_{rgsky} = h_{rgsky}A_g(T_g - T_{sky}) \quad (2)$$

Where h_{rgsky} the radiative heat exchange coefficient between the glass cover and the sky is given by Stefan Boltzmann law:

$$h_{rgsky} = \sigma\varepsilon_w(T_g^2 + T_{sky}^2)(T_g + T_{sky}) \quad (3)$$

The sky temperature is expressed by $T_{sky} = 0.0552(T_a{}^{1.5})$.

The convective heat flux density between the glass cover and the ambient air is expressed by:

$$Q_{cga} = h_{cga}A_g(T_g - T_a) \quad (4)$$

Where h_{cga} the convective heat exchange coefficient between the glass cover and the ambient air is given, as suggested by Ansari, Asbik, Bah, Arbaoui, Khmou (2013) and [Kreith (1967)], by:

$$h_{cga} = 5.8 + 3.8V \quad (5)$$

V is the wind velocity average.

The radiative heat flux density between the brackish water and the glass cover is expressed by:

$$Q_{rwg} = h_{rwg}A_w(T_g - T_w) \quad (6)$$

Where h_{rwg} the radiative heat exchange coefficient between the brackish water and the glass cover is given by:

$$h_{rwg} = \frac{\sigma(T_w^2 + T_g^2)(T_w + T_g)}{\frac{1}{\varepsilon_w} + \frac{1}{\varepsilon_g} - 1} \quad (7)$$

ε_w and ε_g are respectively the brackish water emissivity and the glass cover emissivity and σ is the Stefan-Boltzman constant.

The convective heat flux density between the brackish water and the glass cover is expressed by:

$$Q_{cwg} = h_{cwg}A_w(T_g - T_w) \quad (8)$$

According to [Ansari, Asbik, Bah, Arbaoui, Khmou (2013)] and [Aggarwal and Tiwari (1998)], h_{cwg} the convective heat exchange coefficient between the brackish water and the glass cover is given by:

$$h_{cwg} = 0.884[T_w\text{-}T_g + \frac{(T_w\text{-}T_g)(T_g + 273.15)}{268.9\ 10^3\text{-}P_w}]^{1/3} \quad (9)$$

The evaporative heat flux density between the brackish water and the glass cover is expressed by:

$$Q_{ewg} = h_{ewg}A_w(T_g\text{-}T_w) \quad (10)$$

Following [Ansari, Asbik, Bah, Arbaoui, Khmou (2013)] and [Dunkle (1961)] the evaporative heat exchange coefficient between the brackish water and the glass cover h_{ewg} is given by:

$$h_{ewg} = 16.273\ 10^{-3}h_{cwg}\frac{(P_w\text{-}P_g)}{(T_w\text{-}T_g)} \quad (11)$$

Where P_w and P_g are respectively the water vapor pressures at the brackish water and the glass cover. :

$$P_w = \exp\,(25.317\text{-}\frac{5144}{T_w + 273.15}) \quad (12)$$

$$P_g = \exp\,(25.317\text{-}\frac{5144}{T_g + 273.15}) \quad (13)$$

The absorbed fraction of the incident heat flux density on the glass cover of the solar still P_g is given by:

$$P_g = I_G A_g \alpha_g \quad (14)$$

3.1.2 Thermal energy balance of the brackish water

In the brackish water, the thermal energy balance is expressed by:

$$C_{pw}m_w\frac{dT_w}{dt} = Q_{cbw} - Q_{rwg}\text{-}Q_{cwg}\text{-}Q_{ewg} + P_w \quad (15)$$

The convective heat flux density between the basin liner and the brackish water is written :

$$Q_{cbw} = h_{cbw}A_b(T_b\text{-}T_w) \quad (16)$$

Where h_{cbw} the convective heat exchange coefficient between the basin liner and the brackish water. It is obtained from the correlation of Nusselt number as used by [Ansari, Asbik, Bah, Arbaoui, Khmou (2013)] and [Kreith (1967)]:

Indeed, if $Gr < 10^5$. Nu=1

$$h_{cbw} = \frac{\lambda_w}{L_b} \quad (17)$$

If $10^5 < Gr < 2\ 10^7$, Nusselt number can be determined by the following expression :

$$\mathrm{Nu} = 0.54(\mathrm{Gr\ Pr})^{0.25} \tag{18}$$

If $\mathrm{Gr} > 2\ 10^7$ and Nusselt number is evaluated using the following relation :

$$\mathrm{Nu} = 0.14(\mathrm{Gr\ Pr})^{0.25} \tag{19}$$

The heat transfer coefficient is then computed, for the two latter situations, as :

$$h_{cbw} = \frac{\mathrm{Nu}\ \lambda_w}{L_b} \tag{20}$$

Where Gr, Nu and Pr are respectively the non-dimensionalnumbers Grashof, Nusselt and Prandlt numbers.

The solar power absorbed by the brackish water P_w is given by:

$$P_w = I_G A_w \alpha_w \tau_g \tag{21}$$

The brackish water area should be multiplied by the thickness and the number of baffles

3.1.3 Thermal energy balance of the absorber plate

In the absorber plate, the thermal energy balance is expressed by:

$$C_{pb} m_b \frac{dT_b}{dt} = -Q_{cbw} - Q_{cd} + P_b \tag{22}$$

The conductive heat flux density of the basin is expressed by:

$$Q_{cd} = \frac{\lambda_b}{e_b} A_b (T_b - T_a) \tag{23}$$

λ_b and e_b denote respectively the thermal conductivity and thickness of the absorber plate.

The solar power absorbed by the basin liner P_b is given by:

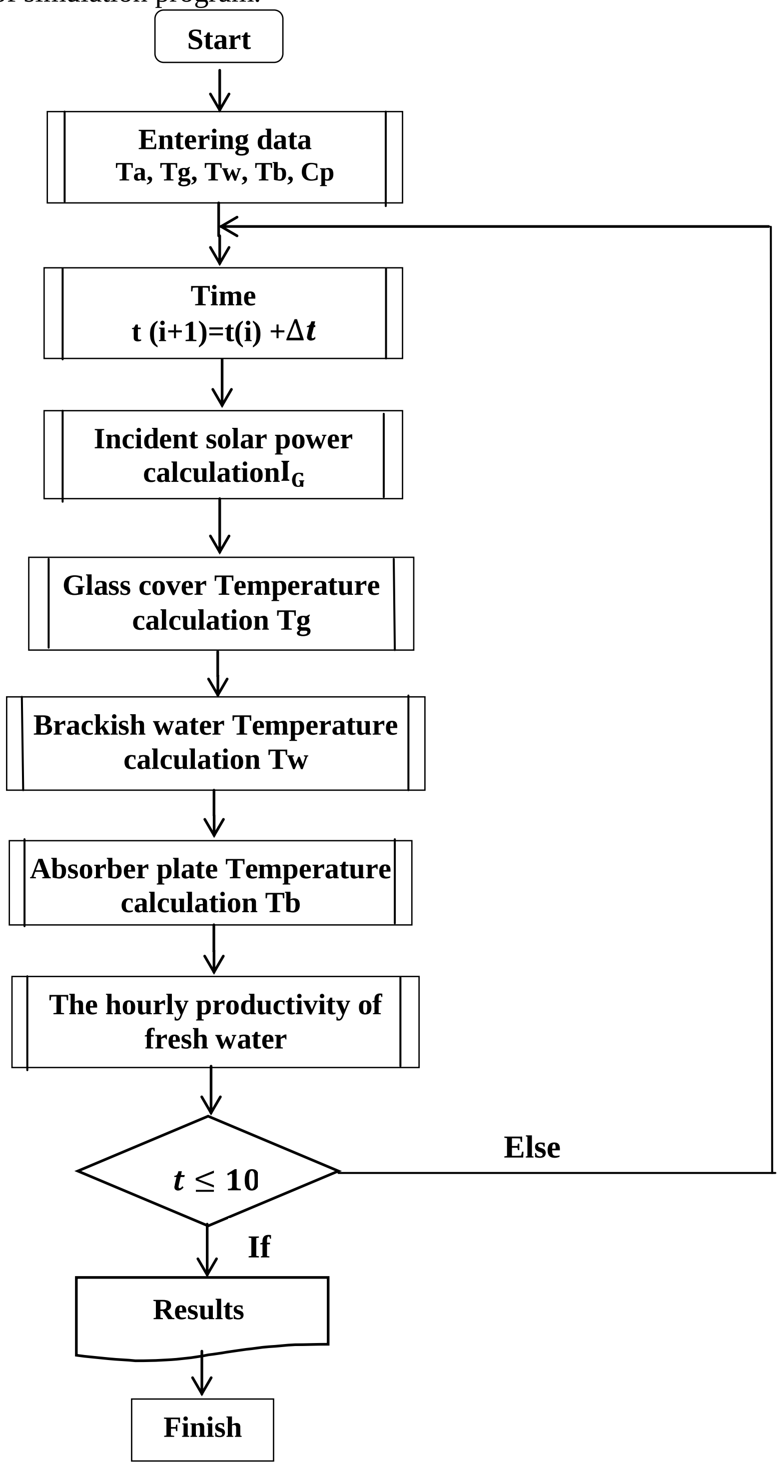
$$P_b = I_G A_b \alpha_b \tau_g \tau_w \tag{24}$$

For the inclined absorber plate the solar radiation absorbed by the basin should be divided by $\sin\alpha$. Where α is the angle of inclination, and was about 35°

In order to keep the same formula of solar radiation for the various elements of solar still, we divided the absorber plate area A_b by $\sin\alpha$

The theoretical analysis are investigated and verified through the experimental results obtained by Montazeri, Banakar and Ghobadian (2013) . This allowed us the validation of the model that could be used to predict the performances of the new designed device.

Ta, Ta+1, Ta+2 are, respectively, the first iteration glass temperature, water temperature and plate temperature. The increase in glass temperature (dT_g), saline water temperature (dT_w), and basin temperature (dT_b) are computed by solving Equations (1), (2) and (3) respectively for stepped still. This iteration is performed for a total duration of 10 hour (36000 second). For the next time step, the parameter is redefined as, $T_g = T_g + dT_g$, $T_w = T_w + dT_w$ and $T_b = T_b + dT_b$. This organization chart presents the main procedure of simulation program.



The design, physical and operating parameters used in theoretical calculation are shown in Tab. 1.

Table 1: Physical parameters used in theoretical calculation

	Specific Heat Cp(J/Kg K)	Thermal Conductivity $\boldsymbol{\lambda}$ (W/m K)	Density $\boldsymbol{\rho(Kg/m^3)}$
Glass	800	1.02	2530
Brackish water	4190	0.67	1022.61
Absorber Plate	896	204	2700

4 Results and discussion

The energy balance equations for various elements of the solar still are formulated and numerically solved by the Runge-Kutta- Fehlber galgorithm, using the dynamic simulation program Matlab/Simulink.

Fig.4 shows an extract of the simulation model created in Matlab/Simulink

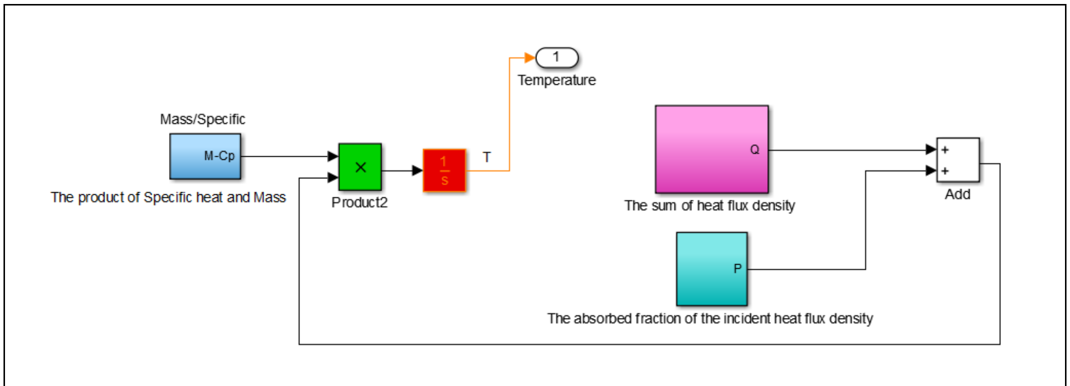


Figure 4: The Simulation model using the dynamic simulation program Matlab/SimulinkTM

We need first to validate the developed mathematical model of the conventional cascade still as experimental results are available in the literature. The quality of simulation program adopted for this study and its capability of predicting the main characteristics of the solar still have also to be confirmed. Therefore a comparison between the simulation program results and the experimental results found by Ahmad Banakar (2013) has been made. The results and data of Ahmad Banakar (2013) are used to validate our analytical model.

Fig.5 illustrates the variation of temperature versus day long for outside environment used in the simulation, in accordance with Ahmad Banakar (2013) data.

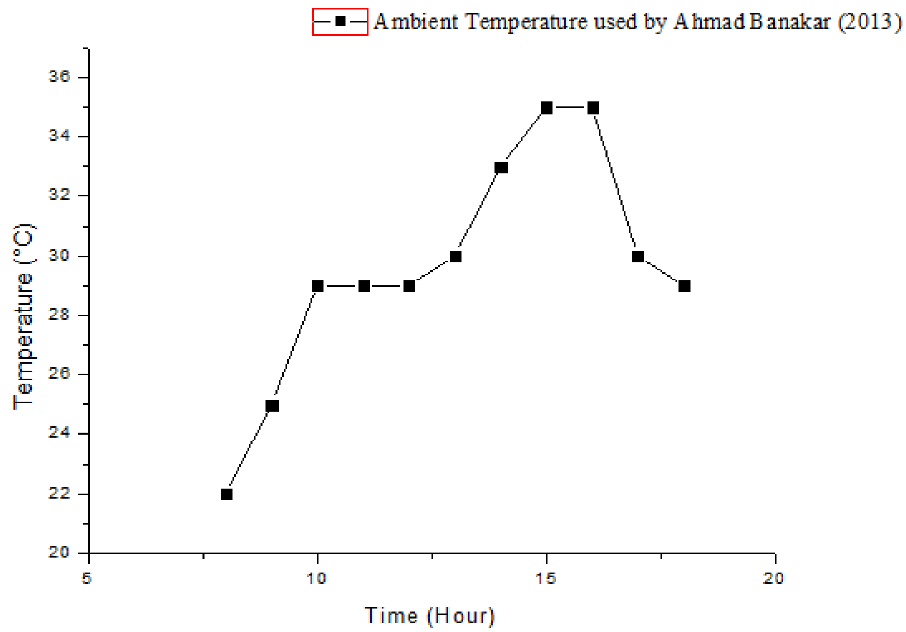


Figure 5: Ambient temperature used in the simulation

The incident solar power I_G is calculated theoretically using physical and geographic parameters of Ahmad Banakar (2013).

Its expression is given by formula (Appendix A.1).

Fig.6 Illustrates the hourly variations of the solar radiation (I_G) calculated by the simulation program.

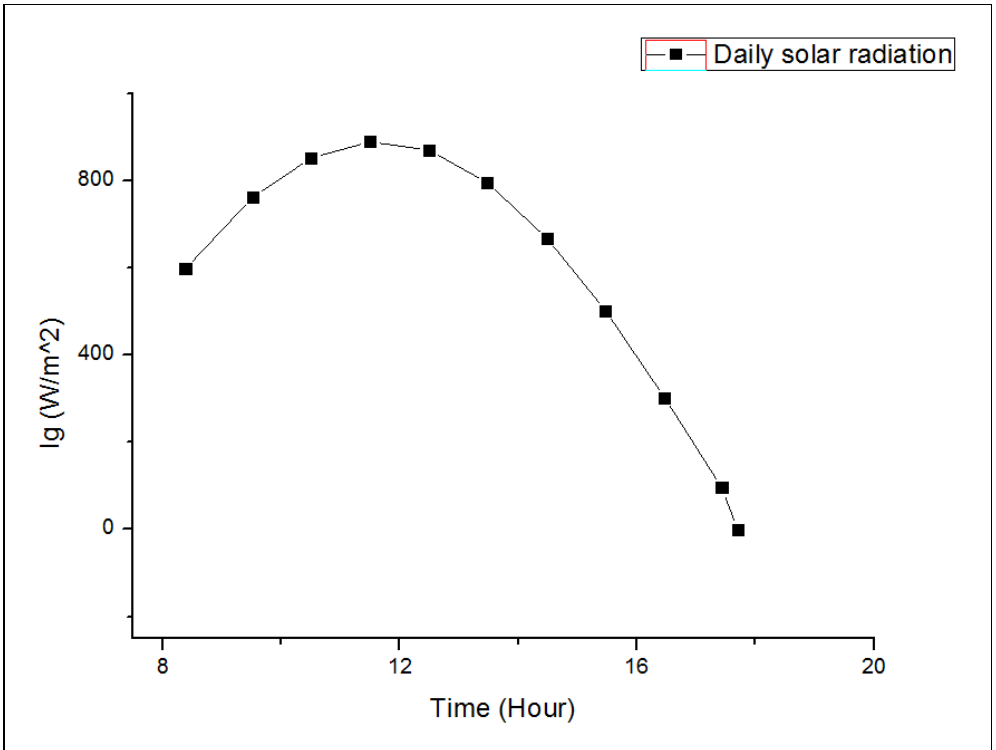


Figure 6: Hourly variation of the solar radiation

Fig.7 depicts the evolution of the absorber plate temperature for the ordinary form of stepped solar still. From these illustrations, it is clear that the curves of the analytical method simulated show similar behavior with those of Ahmad Banakar (2013). As it can be seen from fig.7 there is a good agreement between our thermal analysis and there experimental results.

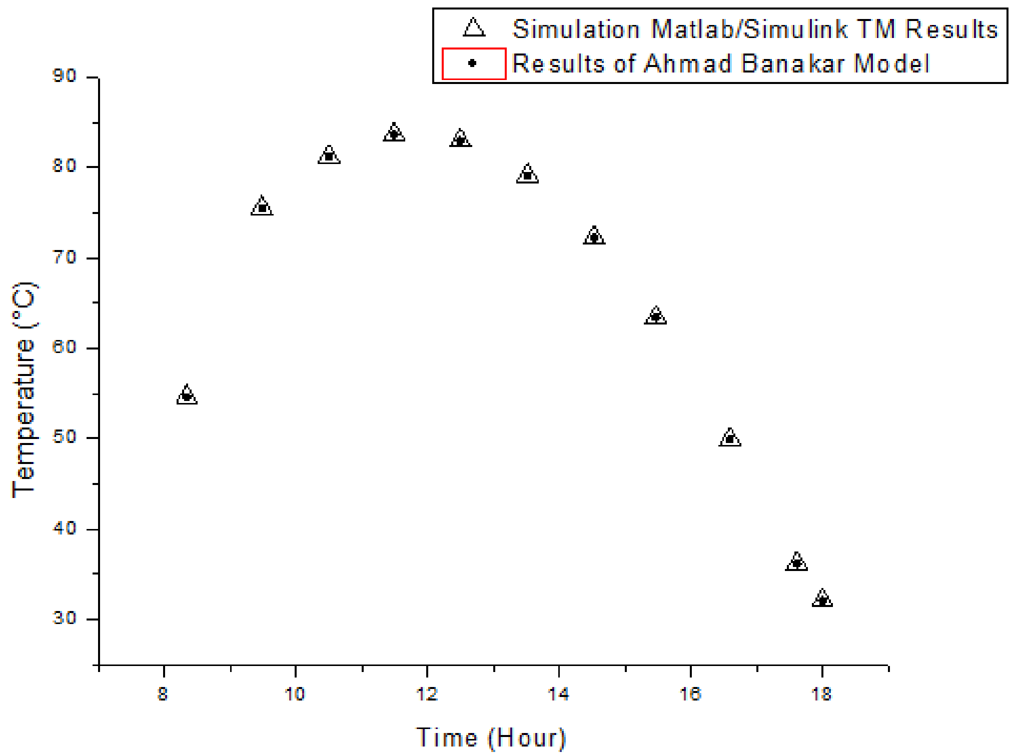


Figure 7: Evolution of the absorber plate temperature for the ordinary form of cascade solar still

As a result of this comparison it can be concluded that our thermal model is well adapted and confirm its capability to simulate the behavior of such an installation..

We then applied this model to the new design we developed consisting in a stepped absorber plate with sloped surfaces and weirs in order to predict its expected performance.

For this reason the thermal results of the new design are compared with the experimental data of the normal form as shown in fig.8.

Fig.8 represents the variation of absorber plate temperature based on the experimental results for the ordinary still and our new design of the absorber plate (stepped absorber plate with slope surfaces and weirs).

The plot indicates that there is a fair agreement between the experimental results of Ahmad Banakar model (normal form of absorber plate) and the theoretical results of the stepped solar still with slope absorber plate and weirs. It is inferred that from fig.8 the absorber plate temperature in the still with slope surfaces and weirs is higher than that of the normal form.

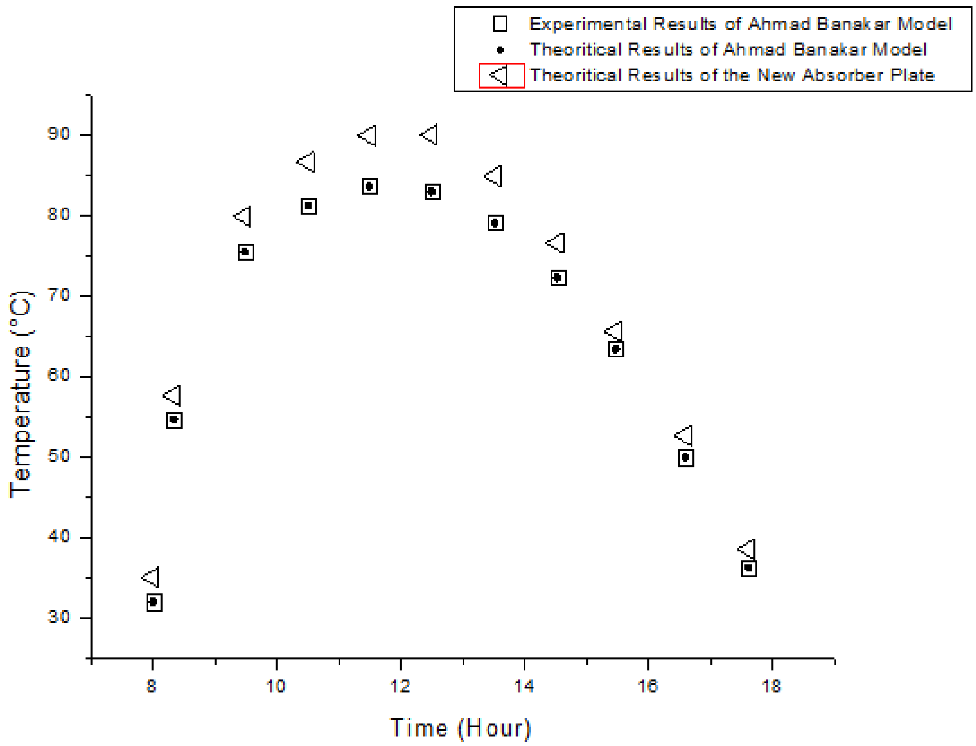


Figure 8: Variation of absorber plate temperature based on experimental results and model results for our new design of the absorber plate (stepped absorber plate with slope surfaces and weirs)

The results show that the new design of absorber plate improves the thermal performance and the hourly productivity of the solar still by at a rate of 1.5% per day.

5 Conclusions

In this paper a new type of absorber plate was developed, tested and fabricated to improve the still productivity.

Firstly a detailed thermal analysis is presented to develop the mathematical model. The energy balance equations are formulated a numerically solved using a simulation program.

Secondly a comparison was done between simulation results and experimental results of the conventional absorber plate. The simulation model was tested in order to validate the quality and the capability of the analytical model.

Thirdly the thermal performance of the new design was also tested, investigated and compared with the experimental results of the ordinary type.

Finally the results show that the new design improves the absorber plate temperature so the thermal performance of a modified stepped solar still can be considerably improved through the new modification. Moreover the absorber plate with sloped surface and weirs more efficient than the conventional type.

So the next phase consists of testing experimentally the device and comparing between experimental and thermal results of the same conception.

Nomenclature

A	Area, m^2
Cp	Specific heat, J $Kg^{-1°}K^{-1}$
h	Heat transfer coefficint, W $m^{-2}K^{-1}$
I_G	Incident solar power, W m^{-2}
Q	Heat flux density, W m^{-2}
m	Mass, kg
t	Temps, hour
δt	Calculation step, hour
T	Temperature, ℃
δT	Incremental rise, ℃
ΔT	Temperature difference, ℃
Greek letters	
ε	Emissivity
α	Absorptivity
τ	Transmissivity
λ	Thermal conductivity, $Wm^{-1}K^{-1}$
Subscipts	
a	Ambient
b	Absorber
c	Convection
cd	Conduction
e	Evaporation
g	Glass
r	Radiation
sky	Sky
w	Brackish water

Appendix

The global incident solar is the summation of the direct radiation and the diffused radiation

$$I_G = I_D + I_d \tag{A.1}$$

The direct radiation I_D is given by formula:

$$I_D = I \times A \times \exp\left[\frac{B}{\sin(h)} \cdot \frac{P}{1000}\right] \times \cos(i) \tag{A.2}$$

Where:

I: Extraterrestrial (outside the atmosphere) irradiance on a plane perpendicular to the Sun's rays (W/m^2)

P: Atmospheric pressure (Pa)

i: Incidence angle of solar radiation (degrees)

h: Angular height of the sun on the horizon.

The diffused radiation I_d is given by formula:

$$I_d = \varphi_1 + \varphi_2 \tag{A.3}$$

Where:

φ_1: Flux emitted by the sky.

φ_2: Flux emitted by the ground.

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