3ème conférence Internationale des énergies renouvelables CIER-2015
Proceedings of Engineering and Technology - PET
pp.64-69

Thermal analysis of cascade solar still

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***Abstract*—The need for production of fresh water from brackish water is considerably high, especially in dry regions. In this paper a new approach to design of solar still absorber plate was developed and its effect 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/SimulinkTM.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 the new modification.**

***Keywords*—Desalination, Brackish water, Stepped solar still, Cascade solar still, Wick type stills.**

I. INTRODUCTION

The available fresh water in the earth is fixed. But the demand of fresh water is increases, due to population growth and rapid industrialization. According to the United Nation in 2025, 63% of the world's population will be living in water scarce areas [1]. The provision of freshwater is becoming a gradually more important issue in many areas of the world. Ocean is the only available source for large amount of water. But the ocean water contains high salinity, so it needs to desalinate the water.

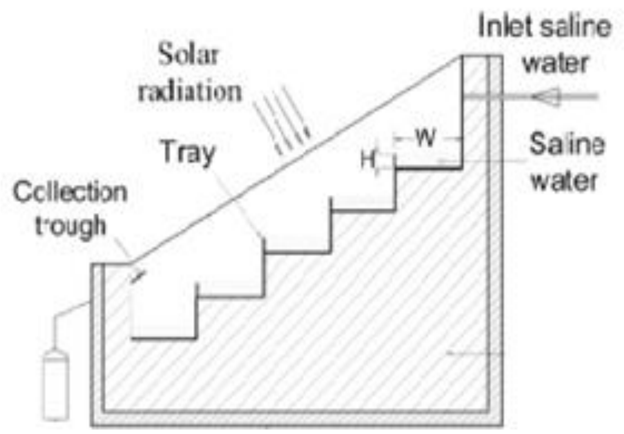
Solar still is widely used in the solar desalination because is a very simple device, easy to fabricate and require only less maintenance. However in comparison with other conventional desalination methods, the yield of the single basin solar still is very low.

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.The solar intensity, wind velocity, ambient temperature cannot be controlled, as they are metrological parameters. Whereas, the remaining parameters can be varied to enhance the productivity of the solar stills.

Depth of water in the solar still inversely affects the productivity of the solar still. Investigations indicated that a reduction of the brine depth in the still improves the productivity, mainly due to the higher basin temperature.

In order to enhance the performance of conventional solar stills, several designs such as wicks [2], plastic water purifier [3], and stepped solar still [4-7].

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



In this study, by developing a mathematical model, a weir-type cascade solar still was designed, tested and compared with the ordinary still.

The still was consisted of a stepped absorber plate with slope surfaces which had an effective

ISSN: 2356-5608

role to absorb solar radiation. Also we added weirs to the absorber plate for heating water quickly.

A comparison between modified stepped solar still and ordinary design created by Ahmed Banakar [8], is carried out to evaluate the developed desalination system performance under the same climate conditions.

II. System Description

The stepped still has the same construction of conventional still; in addition, the absorber plate is made of number of steps as shown in Fig. 1.

Fig. 1 Stepped solar still

The glass temperature and basin water temperature of stepped solar still are higher than that of conventional still. This may be referred to two reasons: (1) a smaller air volume trapped inside the still chamber than in the conventional still and therefore heating up the trapped air will be much faster, and (2) the step-wise basin provides higher heat and mass transfer surface area than the flat basin, thus consequently leads to increase the basin water temperature of stepped solar still, also to increase the evaporation and condensation rate.

The ordinary still had an absorber plate with horizontal and vertical surfaces and the angle between the two surfaces was about 90°. Our pattern as shown in Fig.2 consisted horizontal and vertical/inclined types of absorber plates and the angle between the two surfaces was about 135°. In order to improve the performance of cascade solar still, the flow velocity of the water on the absorber plate should be minimized. Therefore in the new design of slope absorber plate we added different weirs to the surface of absorption.

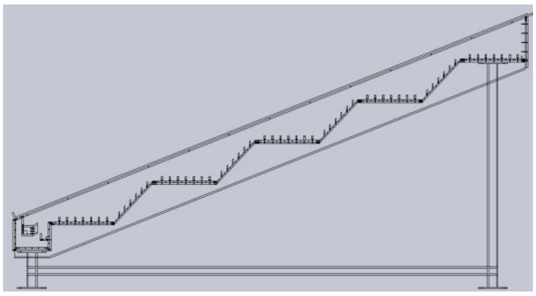


Fig. 2 New design of stepped solar still

III. Mathematical and Thermal Analyses

To evaluate the temperature of the condensing glass cover, 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 leakage air 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.
- Glass has good wettability.
- 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. 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 basin cover glass temperature, water temperature and plate absorber temperature, respectively, all in terms of °C.

A. *Thermal energy balance of the condensing glass cover*

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

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

Where

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

The radiative heat flux density between the glass and the sky;

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

The convective heat flux density between the glass and the ambient air;

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

The radiative heat flux density between the brackish water and the glass;

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

The convective heat flux density between the brackish water and the glass;

- $Q_{ewg} = h_{ewg} A_w (T_g - T_w)$

The evaporative heat flux density from the brackish water surface to the glass cover;

- $P_g = I_G A_g \alpha_g$

The absorbed fraction of the incident heat flux density on the glass cover of the solar still;

B. *Thermal energy balance of the brackish water*

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

$$C_{pw} m_w \frac{dT_w}{dt} = Q_{cbw} - Q_{rwg} - Q_{cwg} - Q_{ewg} + P_w \quad (2)$$

Where

-$Q_{cbw} = h_{cbw} A_b (T_b - T_w)$
The convective heat flux density between the brackish water and the basin;
-$P_w = I_G A_w \alpha_w \tau_g$
The solar power absorbed by the brackish water;

C. Thermal energy balance of the absorber plate

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

$$C_{pb} m_b \frac{dT_b}{dt} = -Q_{cbw} - Q_{cd} + P_b \quad (3)$$

-$Q_{cd} = \frac{\lambda_b}{e_b} A_b (T_b - T_a)$
The convective heat flux density between the absorber and the internal insulation face;
-$P_b = I_G A_b \alpha_b \tau_g \tau_w$
The solar power absorbed by the absorber plate;
λ_b and e_b denote respectively the thermal conductivity and the thickness of the absorber plate;

The theoretical analysis are investigated and verified through the experimental results. 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 total duration of 10 hour (36000 second). The design, physical and operating parameters used in theoretical calculation are shown in Table 1. For the next time step, the parameter is redefined as, $T_g = T_g + dT_g$, $T_w = T_w + dT_w$ and $T_b = T_b + dT_b$.

TABLE I
PHYSICAL PARAMETERS USED IN THEORETICAL CALCULATION

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

IV. RESULTS AND DISCUSSION

The energy balance equations for the various elements of the solar still are formulated and numerically solved, using the dynamic simulation program Matlab/SimulinkTM.

In order to ensure quality of simulation model adopted of this study, its capability of predicting the main characteristics of the solar still has to be confirmed. In the case of the study of a cascade solar still the results of reference [8] and those physical properties are used to validate the mathematical model. Also a comparison between the ordinary form of cascade solar still and the new design of absorber plate was done to evaluate the performance and the capability of the developed design.

Fig.3 shows 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 in Matlab/SimulinkTM have the same behavior like those of reference [8]. As can be seen from fig.3 there is a good agreement between of our thermal analysis and analytical results of reference [8].

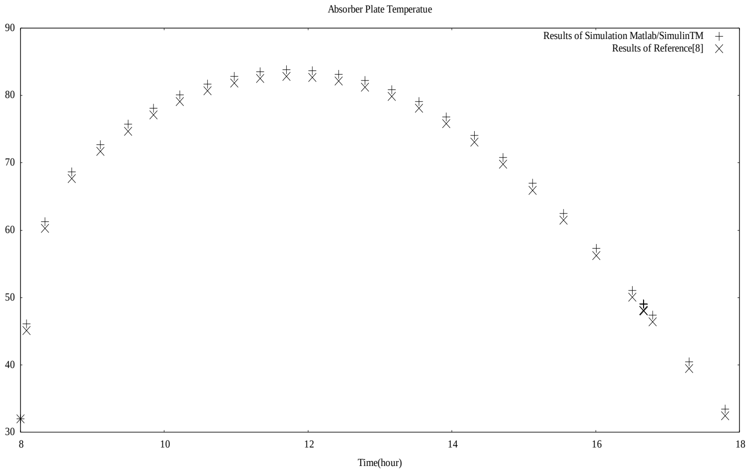
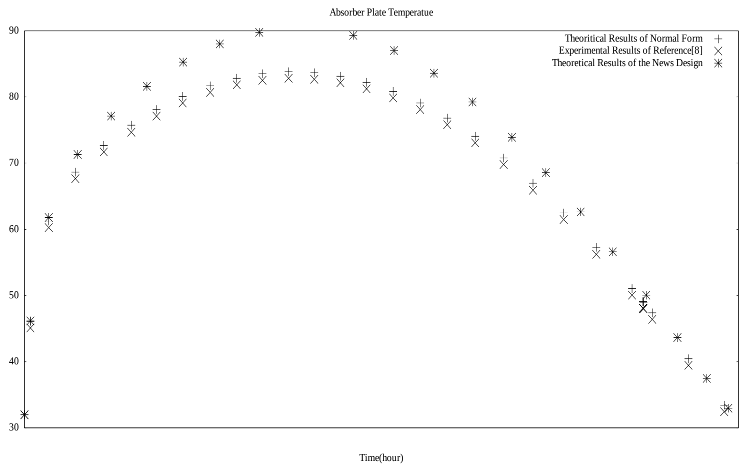


Fig.3.The evolution of the absorber plate temperature for the ordinary form of stepped solar still.

Fig.4 represents the variation of absorber plate temperature based on the model results for the ordinary still and our new design of the absorber plate (stepped absorber plate with slope surfaces



results of the stepped solar still with slope absorber

A	Area, m^2
Cp	Specific heat, J $Kg^{-1}K^{-1}$
h	Heat transfer coefficint, W $m^{-2}K$
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,°C
δT	Incremental rise, °C
ΔT	Temperature difference, °C
Greek letters	
α	Absorptivity
τ	Transmissivity
λ	Thermal conductivity, W$m^{-1}K^{-1}$
Subscipts	
a	Ambient
b	Absorber
c	Convection
cd	Conduction
e	Evaporation
g	Glass
r	Radiation
sky	Sky
w	Brackish water

plate and weirs.

Fig.4. The variation of absorber plate temperature based on experimental results and model results for the ordinary still and our new design of the absorber plate (stepped absorber plate with slope surfaces and weirs).

V. Conclusions

In this paper, an inclined cascade solar still with slope surfaces and weirs in the absorber plate was fabricated to improve the still productivity. A detailed analysis is presented on progress of a prototype.

Also the performance of the still was investigated. The results show that using weirs on each step of still lead to forced flow in inlet water and increases in its residence time. Moreover, the weirs are to keep the water film as shallow as possible.

The average fresh water production for the modified cascade solar still is higher than that of the initial form. So the thermal performance of a modified stepped solar still can be considerably improved through the new modification.

Nomenclature

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