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A Performance Analysis Study of an Active Solar Still Integrating Fin at the Basin Plate

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***Abstract*—**Water is one of the most important and vulnerable natural resources due to human activities and climate change. Water-level continues declining year after year and it is primarily caused by sustained, extensive, and traditional usage methods. Improving water utilization becomes an urgent issue in order satisfy the increasing population needs. Desalination of seawater or brackish water could help in increasing water potential. However, a cost-effective desalination process is required. The most appropriate method for performing this desalination is solar-driven distillation, given its simplicity, low cost and especially the availability of the solar energy source. The main objective of this paper is to demonstrate the influence of coupling integrated basin plate by fins with preheating by solar collector on the performance of solar still. The energy balance equations for the various elements of the solar still are introduced. A numerical example is used to show the efficiency of the proposed solution.

***Keywords*—**Active solar still, Brackisch water, desalination, fins, solar collector.

I. Introduction

THE demand for drinking water is increasing year after year, while natural resources are decreasing due to the population increases and its related activities. This high demand pushes towards searching sophisticated solutions that are very simple, less expensive, and non-polluting. Solar-driven desalination of seawater or brackish water is among the solutions that could help in increasing water potential. Recently, the optimization of the production of distilled water using solar energy has been the subject of numerous experimental and theoretical studies. Among these works, Kabeel et al. in [1] studied experimentally and theoretically the performance of solar still using trays having different depths and widths. The obtained results indicated that the productivity is strongly correlated to both factors, with a 57.3% increase against conventional solar still. Tiwari and his various collaborators [2]-[4], have carried out various studies of both theoretical and experimental nature about the majority effects of the determining parameters and factors on solar desalination, such as ambient temperature, type of solar radiation, depth of water of the basin, solar orientation, the solar slope. Desalination of brackish water using a passive solar distiller integrated by a thermal energy storage system (MCP) has been studied by Ansari et al. [5]. In addition, many researchers have used fins to increase the rate of heat transfer in the solar still; integration of the fins to the basin plate has been studied by El Sebaii et al. in [6], [7]. They found that the productivity increases with the increase of the height of the fins, a rise of 13.7% that of the single distiller.

In this work, we study the effects of the coupling the integrated basin plate by fins, and preheating by solar collector on the performance of the solar still. The energy balance equations for the various elements of the solar still as well as for the preheating are formulated and numerically solved using meteorological conditions that are taken on 15th of June 2016 at the Rabat city (latitude: 34°2’N, longitude: 6°48’W), Morocco. Numerical calculations have been carried using different solar still temperatures and daily distillation mass flow rate. The remainder of this paper is structured as follows. Section 2 introduces the description of the system. In section 3, the mathematical and thermal equations are presented. Section 4 provides a numeral example together with obtained results. Conclusions and perspectives are given in section 6.

II. Mathematical and Thermal Analysis

In this section, we first present the general architecture of the active solar still by integrating fins in the basin of a flat plate (Fig. 1). It includes the following components: 1) Condensing glass cover; 2) Mixture of heated air and steam; 3) Brackish water; 4) Basin liner (Absorber); 5) Fins; 6) Thermal insulation; 7) Non-return valve; 8) Outlet of distilled water; 9) heat exchanger; 10) Feed tank, 11) Brackish water reservoir, 12) Collector. Based on this description, we aim to study the effects of this coupling approach. Mainly, the energy balance equations have to be written to evaluate the temperature of the condensing glass cover, water, and absorber plate and insulation material. We consider that heat losses from the sides of the solar still are negligible; the water layer has a constant thickness of water; the water layer is assumed to be stagnant and its temperature is supposed to be homogeneous on the absorber surface; and the temperature of the water leaving the solar collector is equal to the water temperature at the entrance of solar still. It is worth noting that almost all the physical and geometrical quantities which appear in the thermal energy balance equations are listed in the nomenclature.

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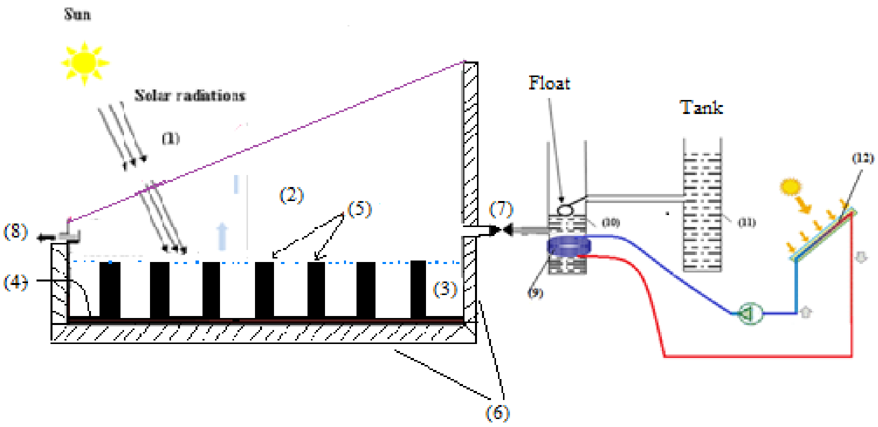

Fig. 1 Active solar still with Integrating fins in the basin of a flat plate

Table I shows the physical properties of the solar still components [5], where Cp, λ, ρ, and d are the specific heat, thermal conductivity, density, and thickness respectively.

TABLE I
PHYSICAL PROPERTIES OF THE SOLAR STILL COMPONENTS

	Cp (J/kg K)	λ (W/m K)	P (kg/m^3)	d (m)
Glass	800	1.02	2530	0.003
Brackish water	4190	0.67	1022.61	0.04
Absorber (aluminum)	896	204	2700	0.002
Heat insulator (fiber glass)	670	0.04	200	0.3

A. Thermal Energy Balance of the Condensing Glass Cover

1. External Face of the Condensing Glass Cover

$$\frac{M_g Cp_g}{2A_g}\frac{dT_{e,g}}{dt} = Q_{cond/glass} - Q_{rad/glass/sky} - Q_{conv/glass/ambient} + \frac{P_g}{2} \quad (1)$$

where $Q_{cond/glass} = \frac{\lambda_g}{d_g}(T_{ig} - T_{eg})$ is the conductive heat flux density between internal and external glass surfaces; $Q_{rad/glass/sky} = h_{rad/glass/sky}(T_{eg} - T_{sky})$ is the radiative heat flux density between the external glass and the sky; $Q_{conv/glass/ambient} = h_{conv/glass/ambient}(T_{eg} - T_a)$ is the convective heat flux density between the external glass and the ambient air; P_g is the solar radiation available on the glass cover of the solar still.

2. Internal Face of the Condensing Glass Cover

$$\frac{M_g Cp_g}{2A_g}\frac{dT_{i,g}}{dt} = Q_{cond/glass} + Q_{rad/water,f/glass} + Q_{conv/water,f/glass} + Q_{evap} + \frac{P_g}{2} \quad (2)$$

where $Q_{rad/water,f/glass} = h_{rad/water,f/glass}(T_{i,g} - T_{w,f})$ is the radiative heat flux density between the brackish water and the internal glass; $Q_{conv/water,f/glass} = h_{conv/water,f/glass}(T_{i,g} - T_{w,f})$ is the convective heat flux density between the brackish water and the internal glass; $Q_{evap} = h_{evap}(T_{i,g} - T_{w,f})$ is the evaporative heat flux density from the brackish water surface to the internal glass cover.

B. Thermal Energy Balance of the Brackish Water

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

$$\frac{M_w Cp_w}{A_w}\frac{dT_{w,f}}{dt} = Q_{conv/basin,f/water,f} - Q_{conv/water,f/glass} - Q_{evap} - Q_{rad/water,f/glass} + Q_{ech} + P_{w,f} \quad (3)$$

where $Q_{conv/basin,f/water,f} = h_{conv/basin,f/water,f}(T_{b,f} - T_{w,f})$ is the convective heat flux density between the brackish water and the finned basin liner;

$$h_{conv/basin,f/water,f} = \left(\frac{h_{cb,eff}A_{b,eff} + h_{cf,eff}A_f\eta_f}{A_w}\right)$$

(See Appendix). $Q_{ech} = K\,S_{ech}(T_f - T_{w,f})$ is the quantity due to the preheating by the solar collector. K: The overall conductance between the heat transfer fluid and brackish water (W / m² °C). S_{ech} : The exchange surface between the heat transfer fluid and brackish water (m²). $P_{w,f}$ is the solar power absorbed by the brackish water with

$$P_{w,f} = \frac{G\tau_g\alpha_w A_{w,eff}}{A_w}$$

For the determination of the effect of the shadow of the fins on the amount of radiation absorbed by the brackish water, we applied the method described by Jaefarzadeh [8] was used to calculate the shadow area due to one fin A_{sh}.written in the following form:

$$A_{sh} = H_f l_{sh} sin\varphi + H_f l_{sh} cos\varphi - l_{sh}^2 sin\varphi\, cos\varphi$$

The total shadow area of the fins $A_{sh,t}$:

$$A_{sh,t} = n_f A_{sh}$$

n_f is number of fins

$$A_{w,eff} = A_w - A_{sh,t}$$

C. Thermal Energy Balance of the Finned Basin Liner

Thermal energy balance of the absorber is given by:

$$M_b Cp_b \frac{dT_{b,f}}{dt} = -Q_{\frac{conv}{basin},\frac{f}{water},f} - Q_{cond/basin,f/i,insulation} + P_{b,f} \quad (4)$$

where $Q_{cond/basin,f/i,insulation} = U_b A_b (T_{b,f} - T_{i,ins})$ is the conductive heat flux density between the finned basin liner and the internal face of the insulation material; $P_{b,f}$ is the solar power absorbed by the finned basin liner; (see Appendix) $U_b = \frac{\lambda_b}{d_b} \lambda_b$ and δ_b are respectively the thermal conductivity and the thickness of the absorber;

D. Thermal Energy Balance of the Insulation Material

In the insulation material, the thermal energy balance equations in the internal and external faces are respectively:

$$\frac{M_{ins} Cp_{ins}}{2A_{ins}} \frac{dT_{i,ins}}{dt} = Q_{cond/basin,f/i,insulation} - Q_{cond/insulation} \quad (5)$$

$$\frac{M_{ins}\ Cp_{ins}}{2A_{ins}} \frac{dT_{e,ins}}{dt} = Q_{cond/insulation} - Q_{rad/e,insulation/soil} - Q_{conv/e,insulation/ambient} \quad (6)$$

where $Q_{cond/basin,f/i,insulation} = \frac{\lambda_b}{d_b}(T_{b,f} - T_{i,ins})$, $Q_{cond/insulation} = \frac{\lambda_{ins}}{d_{ins}}(T_{i,ins} - T_{e,ins})$ is the conductive heat flux density between the internal and external insulation faces; $Q_{rad/e,insulation/soil} = h_{rad/e,insulation/soil}(T_{e,ins} - T_{soil})$ is the radiative heat flux density between the external insulation face and the soil; $Q_{conv/e,insulation/ambient} = h_{conv/e,insulation/ambient}(T_{e,ins} - T_a)$ is the convective heat flux density between the external insulation face and the ambient air.

We note that various heat transfer coefficients which appear in the previous energy balance equations are given in the Appendix.

III. Numerical Results and Discussion

To perform this study and to obtain an allowable design of a solar still system, it is fundamental to collect meteorological data for the site under consideration. In this study, we consider the hourly variations of solar irradiance and ambient temperature (Fig. 2) relative to Rabat city (latitude: 34°2'N, longitude: 6°48'W) these practical data were collected on 15th of June 2016 at the High Normal School Technical Education of Rabat, University Med V-Rabat Morocco.

Before going directly to the heart of the matter and without going into details, we believe that it is necessary to validate our numerical model. Fig. 3 illustrates the comparison between measured and calculated hourly distillation mass flow rate, in the case of the absence of a preheating system, the quantity of pure water produced by a distiller unit is computed as:

$$M_d = \frac{q_{ev}}{A_W\, L_v} = \frac{h_{evap}\, \Delta T\ 3600}{A_W\, L_v} \quad (7)$$

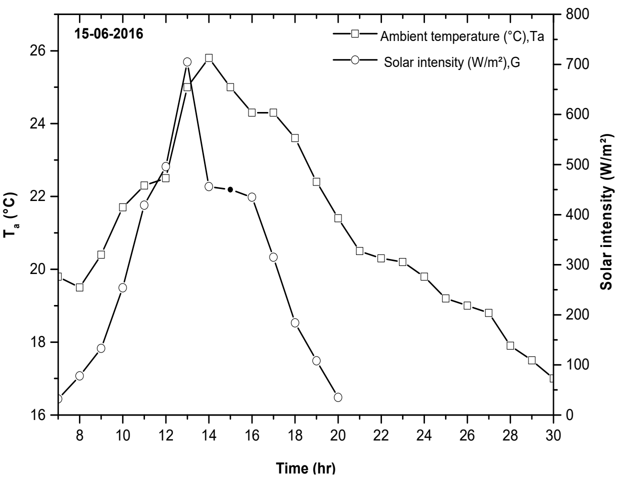

Fig. 2 Hourly variations of the solar radiation (G) and the ambient temperature (T_a)

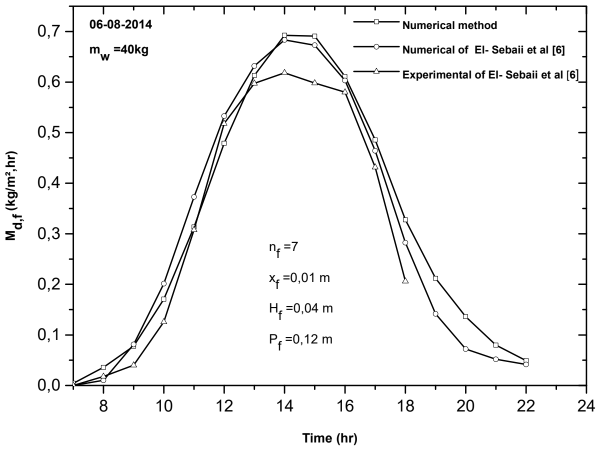

Fig. 3 Validation of the model by comparison between measured and calculated hourly distillation mass flow rate

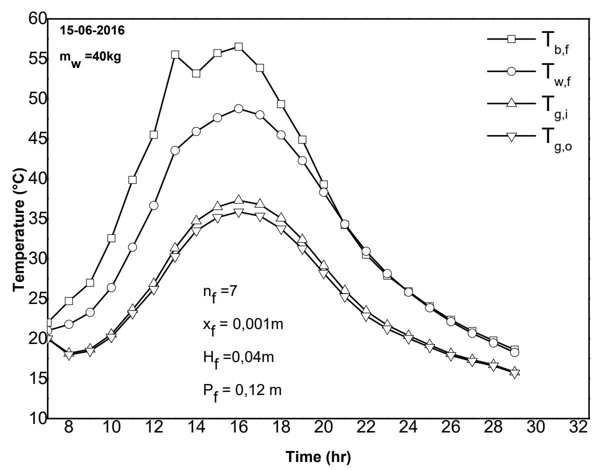

Fig. 4 Hourly variations of temperature for different elements of the solar still with finned basin

This figure confirms the results reported in the literature [6]. Hourly variations of temperature for different elements of the solar still with finned basin on 15 Jun 2016 when nf =7 and mw=40 kg are shown in Fig. 4. The results of this figure are exhibiting the same behavior of solar radiation with shift of peak positions due to the thermal inertia of the still elements and basin water. The basin liner temperature is higher than that of basin water during sunshine hours. The maximum values of Tp,f, Tw.f, Tig, and Teg, are obtained as 56.4, 49, 37.14 and 35.96 °C, respectively.

Fig. 5 highlights the hourly variations of the brackish water temperature T_w for three cases: simple solar still, only with finned-basin and this last with preheating. It is generally observed that the temperatures at all points increase as the time passes until a maximum value which is reached around 4:00 pm and begin to decrease after that. This behavior is more expressed in the presence of the system with fin and preheating at the same time. Fig. 6 illustrates the effect of the fins and the preheating, on the hourly variations of daily distillation mass flow rate, it is clear that the quantity produced by the solar still with fins and preheating is higher than the other cases, simple and with fins, are obtained as 2.75 2.2 and 2.4 kg/m² day, respectively.

IV. Conclusion and Perspectives

This paper introduced a comparison of the production of distilled water between a passive and an active solar still integrated fin to the basin liner, after analyzing the results, we can conclude: the integration fin to the basin liner still with the use of the preheating system at the same time, significantly improves the productivity of fresh water of the distillation system.

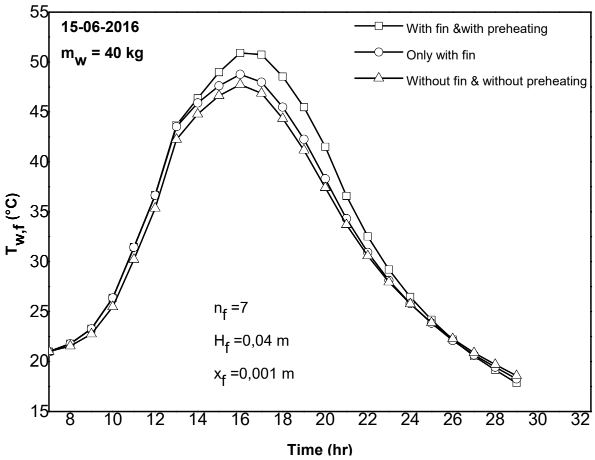

Fig. 5 Influence of fins and preheating on the hourly variations of brackish water temperature T_w

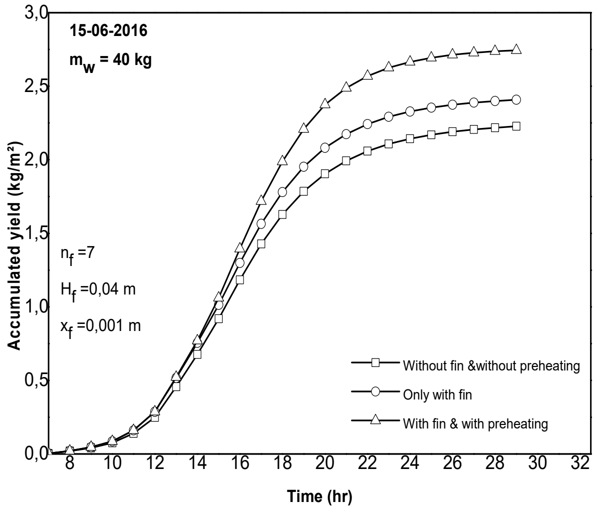

Fig. 6 Influence of fins and preheating on the hourly variations of daily distillation mass flow rate

Nomenclature

A	Surface area, m^2
$A_{b,eff,sh}$	effective area of the absorber plate in the presence of shadow due to fins (m²)
C	Specific heat, J $kg^{-1}K^{-1}$
d	Thickness, m
h	Heat transfer coefficient, W $m^{-2}K^{-1}$
hevap	Evaporation heat transfer coefficient, W $m^{-2}K^{-1}$
G	Incident solar power, W m^{-2}
K	Thermal conductivity (W/m.K)
Lv	Latent heat of vaporization, J kg^{-1}
Pk	Power absorbed by the element k, W m^{-2}
Q	Heat flux density, W m^{-2}
M	Mass, kg
Md	Hourly distillation mass flow rate, kg $m^{-2}h^{-1}$
t	Temps, hour
T	Temperature, °C
ΔT	Temperature difference, °C
V	Wind velocity average
l_f	Length of the fin
H_f	Height of fins
$G_{f,l}$	Solar radiation incident on the left of fins
$G_{f,r}$	Solar radiation incident on the right of fins
η_f	Fin efficiency
Greek letters	
α	Absorptivity
λ	Thermal conductivity, W $m^{-1}K^{-1}$
ε	Emissivity
η	Thermal efficiency %
ρ	Density, kg m^{-3}
σ	Stefan–Boltzmann constant
τ	Transmissivity
Subscripts	
a	Ambient
b	Absorber
conv	Convection
cond	Conduction
e	External
eff	Effective
evap	Evaporation
f	Fins
g	Glass

i	Internal
ins	Insulation
l	Liquid
rad	Radiation
sh	Shadow
sky	Sky
soil	Soil
w	Brackish water

Appendix

A. Various Heat Exchange Coefficients

- $h_{conv/glass/ambient} = 5.8 + 3.8\,V$
- $h_{rad/glass/sky} = \sigma\varepsilon_g\left(T_{eg}^2 + T_{sky}^2\right)\left(T_{eg} + T_{sky}\right)$
- $h_{rad/water,f/glass} = \dfrac{\sigma\left(T_w^2+T_{ig}^2\right)\left(T_w+T_{ig}\right)}{\frac{1}{\varepsilon_w}+\frac{1}{\varepsilon_g}-1}$
- $h_{conv/water,f/glass} = 0.884\left[T_w - T_{ig} + \dfrac{(P_w-P_g)(T_{ig}+273.15)}{298.9\,10^3-P_w}\right]^{1/3}$
- $h_{evap} = 16.273\,10^{-3} h_{conv/water,f/glass}\dfrac{(P_w-P_g)}{(T_w-T_{ig})}$

Water vapor pressures at the brackish water and the internal glass cover are:

$$P_w = \exp\left(25.317 - \frac{5144}{T_w + 273.15}\right)$$

$$P_g = \exp\left(25.317 - \frac{5144}{T_g + 273.15}\right)$$

- $h_{conv/basin,f/water,f} = \left(\dfrac{h_{cb,eff}A_{b,eff}+h_{cf,eff}A_f\eta_f}{A_w}\right)$

where

$$A_{p,eff} = n_f P_f\, l$$
$$A_f = 2n_f H_f l_f$$
$$\eta_f = \frac{tanh\sqrt{2h_{cfw}H_f/K_f\delta_f}}{2h_{cfw}H_f/K_f\delta_f}$$

$$h_{rad/e,insulation/soil} = \sigma\varepsilon_{ins}\left(T_{e,ins}^2 + T_{soil}^2\right)\left(T_{e,ins} + T_{soil}\right)$$

B. Solar Power Absorbed by Various Elements of the Active Solar Still

- By the glass cover

$$P_g = G\alpha_g$$

- By the finned basin liner

$$P_{b,f} = G_{bf}\tau_g\tau_w\alpha_b$$

where

$$G_{bf} = \left(G_{f,l}\frac{A_f}{2}\right) + \left(G_{f,r}\frac{A_f}{2}\right) + \left(GA_{b,eff,sh}\right)$$
$$A_{b,eff,sh} = A_{b,eff} - A_{sh,t}$$

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