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Theoretical and experimental analysis of pin fins absorber solar still

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ABSTRACT

Over the past decade, the demands for fresh water and energy are growing faster than ever. The use of renewable energy, for seawater and brackish water desalination, is increasing and is currently under the spot light of international conferences. This article presents a theoretical and experimental work performed on a solar still with a pin fins absorber plate. In this work, a conventional active solar still, with a basin area of 0.5 m^2 and a glass cover at an inclination of 30˚ to the horizontal fixed on the top part of the still, has been designed, and tested with conventional absorber plate (thin-layer absorber plate), and pin fins absorber plate under the same climatic condition. Desalination of the brackish water using a solar still with conventional absorber plate and pin fins absorber plate is theoretically and experimentally compared. The heat transfer energy balance equations for the various elements of the active solar still are formulated, numerically solved, and validated. The experiments were conducted in the High Institute of Technological studies of Gafsa, Tunisia, during two successive winter days, 21 and 22 January 2014, respectively, for the conventional and modified solar still. The results show that using the pin fins absorber plate in the active solar still increases the daily productivity by 12%.

Keywords: Desalination; Solar still; Solar energy; Modified still

1. Introduction

As the world's population grows in number and riches, the demands for water and energy are increasing faster than ever [1]. Fresh water is a basic human need for living, development, and economical progress; approximately 71% of the earth's surface is covered with water. Unfortunately, 97% of this water is salt water in seas and oceans. This amount of water is not directly available for use. Regional shortages of potable water become more prevalent in many developing countries, and safely drinkable water remains inaccessible for about 1.1 billion people in the world [2,3]. Because of this, research, development, and optimization of desalination system are fundamental for human life. Solar stills have long been the simplest way and a good technological solution of using solar radiation to produce fresh water. This constitutes a viable option in

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places where other water sources are limited or unavailable [4–6].

Solar still is a simple device that takes heat from solar radiation to evaporate salt water. After, it returns this heat to the environment, that is, when vapor condenses onto the transparent covers [7]. The productivity of the solar still is very small compared with the expensive technologies for desalination systems such as reverse osmosis, vapor compression, solvent extraction, phase change, ion exchange, and electrodialysis. The production capacity of a simple type still is in the range of 2–5 $l/m^2/d$ [8,9].

Several experimental and numerical researches have been developed in order to enhance the productivity and the thermal efficiency of the solar stills by improving design [10–12] and changing parameters such as orientation and glass cover inclination [13–15]. The productivity of the active solar still can also be increased by adding other devices such as using internal and external reflectors [14–17], adding heat energy storage system [18,19], using photovoltaic energy [20,21].

The aim of the present work is to analyze the use of pin fins absorber plate in the solar still. The pin fins increase the surface area of the absorber in contact with water; hence, absorber–basin water heat transfer and basin water temperature increased witch conduct to improve the productivity. The modified solar still is compared to the conventional one. Thus, a conventional active solar still with a basin area of 0.5 m^2, and a 30˚ inclination glass cover to the horizontal has been designed, manufactured, and tested with conventional absorber plate (thin-layer absorber plate), and pin fins absorber plate under the same climatic condition.

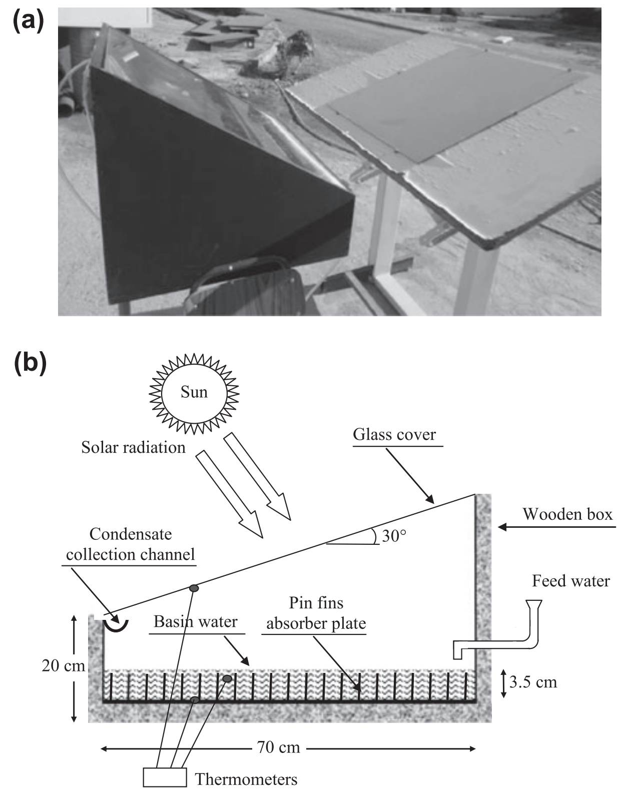

Fig. 1. (a) Solar still with moving mirror. (b) Cross-section of a solar still experimental setup.

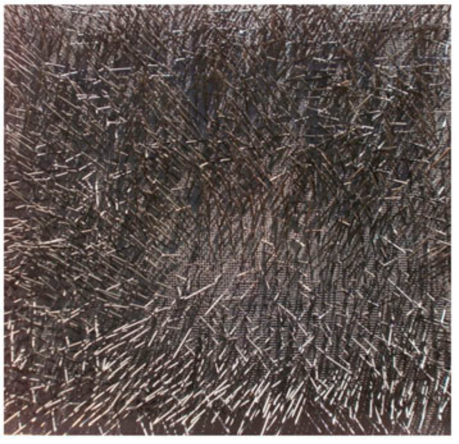

Fig. 2. Pin fins absorber plate.

2. System description

Fig. 1(a) and (b) show, respectively, a picture and a schematic diagram of the solar still experimental setup. In this work, solar still of 0.5 m^2 of surface area was designed and made of plywood, covered with polystyrene in inner sides and painted black to reduce the vapor condensation on the walls. A glass cover at an inclination of 30˚ to the horizontal fixed on the top part of the still. Moving mirror was used to collect and reflect more solar energy on the still box. Two types of absorber plate are made: a simple thin layer of absorber plate painted black and a pin fins absorber plate painted black (Fig. 2). The pin fins are black-painted steel rods with a diameter of 0.3 cm and a length of 6 cm, and also spaced from each others by 1.5 cm. The absorber plate was placed horizontally inside the box to optimize absorption of solar radiation. The basin is filled by brackish water which is heated by solar radiations passed through the glass cover. Then, vapor flows upward and condenses when it gets into contact with the inner side of the glass cover. This is due to the effect of the temperature difference between the brackish water surface and the inner glass cover surface.

3. Error analysis

The measured experimental data generally include some errors due to the uncertainty of the measuring process and the limited precision of the experimental instruments. These measured errors may affect the accuracy of results. The minimum error occurred in an instrument is equal to the ratio between its least count and minimum value of the output measured [22,23]. Thermometer, flask, and solarimeter are used for measuring temperature, distilled collection, and solar intensity, respectively. The accuracies of these instruments used in the experiments are given in Table 1.

Table 1
Accuracies and errors for measuring instruments

Instrument	Accuracy	Range	% Error
Solarimeter	±10 W/m^2	0–2,000 W/m^2	5
Digital thermometer	±0.1°C	−50 to 300°C	0.25
Calibrated flask	±5 ml	0–250 ml	5

4. Mathematical model of the present system

Several assumptions are made to establish the energy balances of the solar still.

(1) The level of water in the basin is maintained constant.
(2) Water layer temperatures are supposed homogeneous.
(3) The solar still is vapor-leakage proof.
(4) Glass cover temperature is supposed homogeneous.
(5) Absorber plate temperature is supposed homogeneous.

Fig. 3 shows the principle of heat transfer mechanisms in the solar still. The energy balance equation for the glass covers, the brackish water, and the basin plate of the solar still can be written as follows:

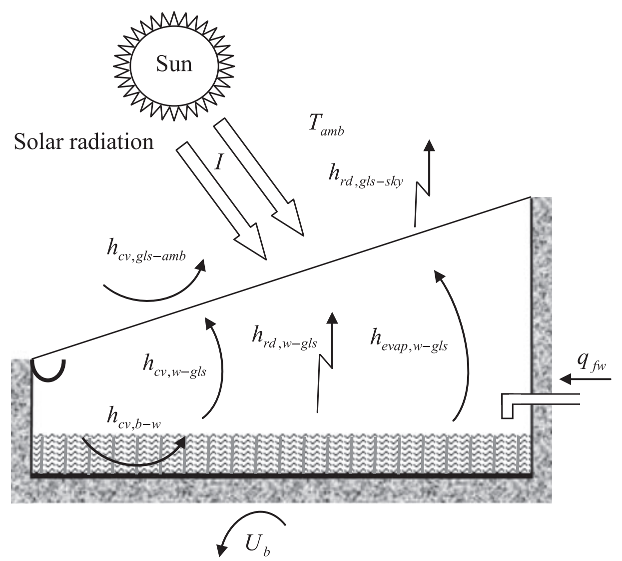

Fig. 3. Schematic diagram of heat transfer mechanisms in the solar still.

4.1. Thermal energy balance of the glass cover

$$\frac{m_{\rm gls}C_{\rm p,gls}}{A_{\rm gls}}\frac{{\rm d}T_{\rm gls}}{{\rm d}t} = F_{\rm gls}\cdot I + q_{\rm cv,w-gls} + q_{\rm evap,w-gls} + q_{\rm rd,w-gls} - q_{\rm rd,gls-sky} - q_{\rm cv,gls-amb} \tag{1}$$

4.2. Thermal energy balance of the brackish water

$$\frac{m_{\rm w}C_{\rm p,w}}{A_{\rm w}}\frac{{\rm d}T_{\rm w}}{{\rm d}t} = F_{\rm w}\cdot I + q_{{\rm cv},b-{\rm w}} - q_{{\rm cv},w-{\rm gls}} - q_{\rm evap,w-gls} - q_{\rm rd,w-gls} - q_{\rm fw} - q_{\rm loss,sw-amb} \tag{2}$$

4.3. Thermal energy balance of the basin

$$\frac{m_bC_{{\rm p},b}}{A_b}\frac{{\rm d}T_b}{{\rm d}t} = F_b\cdot I - q_{{\rm cv},b-{\rm w}} - q_{{\rm loss},b-{\rm amb}} \tag{3}$$

In this study, the emissivity and absorptivity of the pin fins are assumed equal to 1. Then, the values of the solar absorption factor F are given by [24,25]:

$$F_{\rm gls} = \alpha_{\rm gls} \tag{4}$$

$$F_{\rm w} = \alpha_{\rm w}\tau_{\rm gls} \tag{5}$$

$$F_{\rm abs} = \alpha_b\tau_{\rm gls}(1-\alpha_{\rm w}-\rho_{\rm w}) \tag{6}$$

The evaporative and convective heat transfer flux density between brackish water and glass cover are given by:

$$q_{\mathrm{evap,w-gls}} = h_{\mathrm{evap,w-gls}}(T_{\mathrm{w}} - T_{\mathrm{gls}}) \tag{7}$$

$$q_{\mathrm{cv,w-gls}} = h_{\mathrm{cv,w-gls}}(T_{\mathrm{w}} - T_{\mathrm{gls}}) \tag{8}$$

The convective and the evaporative correlation between the water surface and the glass cover were initially proposed by Dunkle correlation [26] to estimate the heat and mass transport in a closed solar still. The proposed mathematical model assuming that the driving force for the convective heat transfer is enhanced beyond the level imposed by the temperature differential as occurs in ordinary thermal systems. The correlation was derived under the assumption of the still temperatures often exceeds 50℃ and negligible partial vapor pressures. The evaporative and convective heat transfer coefficient between water and glass cover can be given by [7,10,27]:

$$h_{\mathrm{evap,w-gls}} = 16.173 \times 10^{-3} \cdot h_{\mathrm{cv,gls-w}} \frac{(P_{\mathrm{w}} - P_{\mathrm{gls}})}{(T_{\mathrm{w}} - T_{\mathrm{gls}})} \tag{9}$$

$$h_{\mathrm{cv,w-gls}} = 0.884 \left[(T_{\mathrm{w}} - T_{\mathrm{gls}}) + \frac{(P_{\mathrm{w}} - P_{g}) \cdot T_{\mathrm{w}}}{268,900 - P_{\mathrm{w}}} \right]^{\frac{1}{3}} \tag{10}$$

The convective heat transfer flux density between the glass cover and the ambient is given by:

$$q_{\mathrm{cv,gls-amb}} = h_{\mathrm{cv,gls-amb}}(T_{\mathrm{gls}} - T_{\mathrm{amb}}) \tag{11}$$

The heat loss transfer coefficient between the glass cover and the environment is given by [24]:

$$h_{\mathrm{cv,gls-amb}} = 2.8 + 3 \cdot u_{\mathrm{wind}} \qquad u_{\mathrm{wind}} \leq 5\,\mathrm{m\,s^{-1}} \tag{12}$$

$$h_{\mathrm{cv,gls-amb}} = 6.15 \cdot u_{\mathrm{wind}}^{0.8} \qquad u_{\mathrm{wind}} > 5\,\mathrm{m\,s^{-1}} \tag{13}$$

where u_{wind} is the average wind velocity.

The convective heat transfer flux density between basin and brackish water is given by:

$$q_{\mathrm{cv},b-\mathrm{w}} = h_{\mathrm{cv},b-\mathrm{w}} \cdot (T_b - T_{\mathrm{w}}) \tag{14}$$

The convective heat transfer coefficient between basin and water, $h_{\mathrm{cv},b-\mathrm{w}}$ is taken as 120 W/m^2 K, for the conventional one and 150 for the pin fins absorber plate.

The flux density of the radiative heat transfer between the brackish water and the glass cover is given by:

$$q_{\mathrm{rd,w-gls}} = h_{\mathrm{rd,w-gls}}(T_{\mathrm{w}} - T_{\mathrm{gls}}) \tag{15}$$

The radiative heat transfer coefficient between glass cover and brackish is given by Duffie and Beckman [25]:

$$h_{\mathrm{rdw-gls}} = \sigma \cdot \varepsilon_{\mathrm{gls-w}} \cdot \left(T_{\mathrm{gls}}^2 + T_{\mathrm{w}}^2\right) \cdot (T_{\mathrm{gls}} + T_{\mathrm{w}}) \tag{16}$$

where

$$\varepsilon_{\mathrm{gls-w}} = \left(\frac{1}{\varepsilon_{\mathrm{gls}}} + \frac{1}{\varepsilon_{\mathrm{w}}} - 1 \right)^{-1} \tag{17}$$

The flux density of the radiative heat between the brackish water and the internal glass is given by:

$$q_{\mathrm{rd,gls-sky}} = h_{\mathrm{rd,gls-sky}}(T_{\mathrm{gls}} - T_{\mathrm{sky}}) \tag{18}$$

The radiative heat transfer coefficient between glass and sky is given by Duffie and Beckman [25],

$$h_{\mathrm{rd,gls-sky}} = \sigma \cdot \varepsilon_{\mathrm{gls}} \cdot \left(T_{\mathrm{gls}}^2 + T_{\mathrm{sky}}^2\right) \cdot (T_{\mathrm{gls}} + T_{\mathrm{sky}}) \tag{19}$$

The sky temperature is suggested to be related to the local absolute air ambience temperature by the simple relation [28]:

$$T_{\mathrm{sky}} = 0.0552\, T_{\mathrm{amb}}^{1.5} \tag{20}$$

The feed water takes heat from basin, the heat taken by the replaced water is estimated by:

$$q_{\mathrm{fw}} = \dot{m}_{\mathrm{fw}} C_{\mathrm{p,fw}} \cdot (T_w - T_{\mathrm{fw}}) \tag{21}$$

The heat losses by convection through the side wall to surrounding are given by:

$$q_{\mathrm{loss,sw-amb}} = A_{\mathrm{sw}} \cdot U_{\mathrm{sw}} \cdot (T_{\mathrm{w}} - T_{\mathrm{amb}}) \tag{22}$$

The heat losses by convection through the basin base to the ground and surrounding are given by:

$$q_{\mathrm{loss},b-\mathrm{amb}} = A_b \cdot U_b \cdot (T_b - T_{\mathrm{amb}}) \tag{23}$$

5. Numerical and experimental results and discussion

Numerical and experimental results were performed to evaluate the performance of the solar still compared to the conventional one under the outdoors climatic conditions of Gafsa—Tunisia. The numerical results for the solar still are obtained by solving the energy balances of the mathematical model. The experiments were conducted in the High Institute of Technological Studies of Gafsa in the south of Tunisia during two successive winter days, 21 and 22 January 2014, respectively, for solar still with the conventional absorber plate and modified solar still with pin fins absorber plate. The tests started around 8:30 am to 6 pm. Ambient temperature, brackish water temperature, glass cover temperatures, and solar radiation were taken every 60 min. The water depth in the basin is maintained at 3.5 cm.

Fig. 4 shows the ambient temperature and solar radiation during the two successive testing days, 21 January 2014 testing the conventional solar still with the thin-layer absorber plate and 22 January 2014 testing the modified solar still with the pin fins absorber plate. Therefore, the solar radiation and temperature profiles, respectively, for the two testing days are approximately the same with too little differences. Then, we assumed that the conventional and modified solar stills are experienced at the same climatic conditions. Hence, the results for the two types can be compared.

Fig. 5 illustrates the experimental water and glass temperature of the modified still and the conventional one. It is noticed that the brackish water and glass cover temperatures of the conventional solar still are lower than those for the modified solar still. Figs. 6 and 7 show, respectively, the experimental and numerical results of the variation of the brackish water temperature and glass cover temperature of modified and conventional solar still. It is observed that the temperatures of the two solar stills augment as the solar radiation increases until they achieve their maximum values around midday and then diminish with the decrease of solar radiation.

Fig. 8 illustrates the experimental results of the of fresh water productivity variation per unit area during the two testing days. It can be noted that the fresh water productivity for the second day, solar still with pin fins absorber plate, is greater than that of first day, conventional absorber plate. It can be observed that maximum productivity occurs at maximum temperature of the brackish water. Also, it is found that the daily productivity of the modified solar still is increased by 12% with regard to the conventional one.

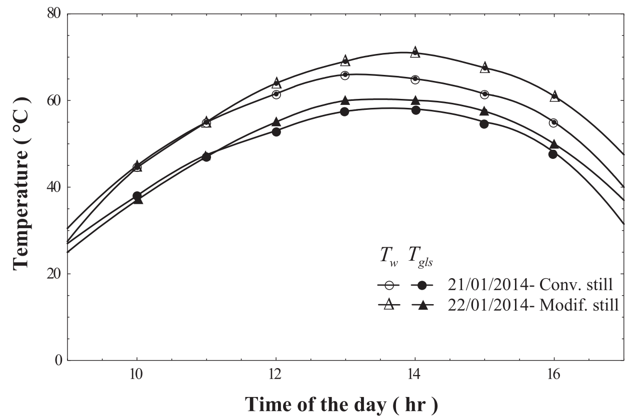

Fig. 5. Experimental temperature variations of water and glass for the modified and conventional still.

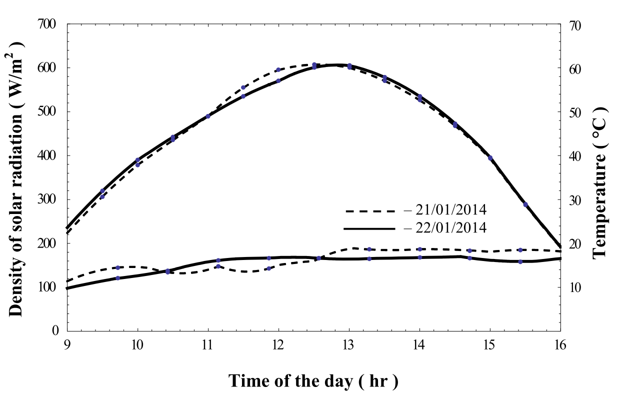

Fig. 4. Hourly ambient temperature and solar radiation during the two testing days.

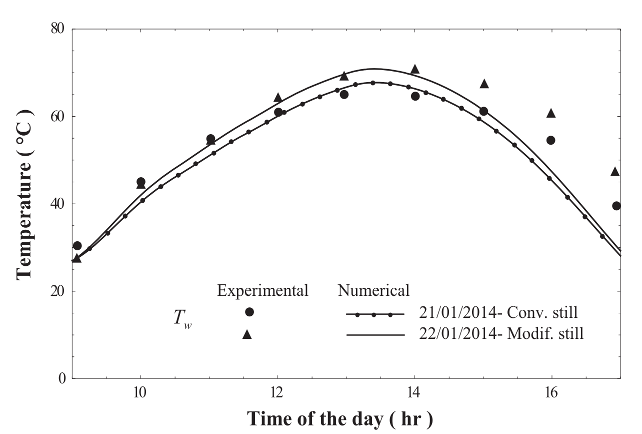

Fig. 6. Experimental and numerical temperature variations of brackish water for the two solar stills.

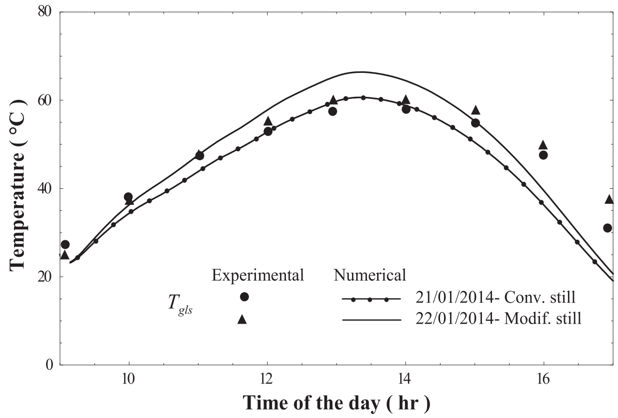

Fig. 7. Experimental and numerical temperature variations of glass cover for the two solar stills.

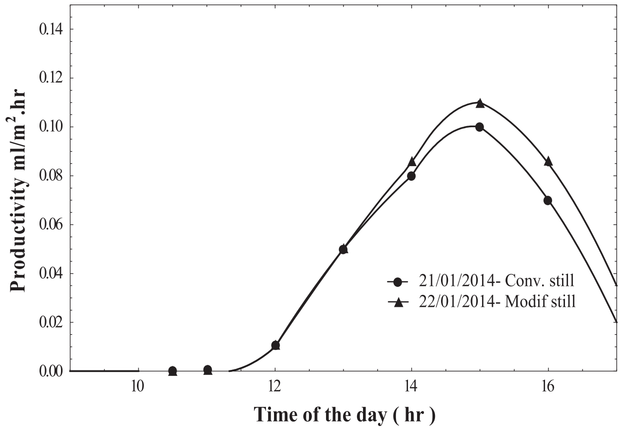

Fig. 8. Variation of fresh water productivity for the two solar stills.

6. Conclusion

On the basis of this work, the following conclusions and recommendations can be inferred:

(1) A conventional active solar still is manufactured and tested with two types of absorber plate under the same climatic conditions.
(2) Water and glass cover temperatures of the conventional and modified solar still are theoretically predicted and validated experimentally.
(3) Experimental and theoretical studies show that performance of still with pin fins absorber plate is better than the conventional one. However, the performance difference between conventional and modified solar still is small. This is due to the little difference between their surface areas exchange. The heat and mass transfer is enhanced when surface exchange is increased.
(4) The daily productivity of the still with pin fins absorber plate is increased by 12% compared to the conventional one.
(5) The simple design and manufacturing of the active solar still with integrated condenser permits a simple way to provide fresh water for drinking and domestic applications.
(6) Many parameters should be optimized to increase the performance of a solar still such as basin water depth, shape, design, wind velocity, weather conditions, insulations, etc.
(7) The system can be used to produce fresh water to satisfy the need for domestic use with a low operation and maintenance cost.

Nomenclature

A	—	area, m^2
C_p	—	specific heat, J kg^{-1} K^{-1}
F	—	solar radiation absorption factor
h	—	heat transfer coefficient, W m^{-2} K^{-1}
I	—	incident solar power, W m^{-2}
m	—	mass, kg
T	—	temperature, K
t	—	time, s
q	—	heat flux density, W m^{-2}
u	—	velocity, m s^{-1}

Greek letters

α	—	absorptivity
τ	—	transmissivity
ρ	—	reflectance
σ	—	Stefan–Boltzmann constant
ε	—	emissivity

Subscripts

amb	—	ambient
b	—	absorber
cv	—	convection
evap	—	evaporation
fw	—	feed water
gls	—	glass
loss	—	loss
rd	—	radiation
sky	—	sky
sw	—	side well
w	—	brackish water

References

[1] M.H. Sellami, H. Bouguettaia, D. Bechki, M. Zeroual, S. Kachi, S. Boughali, B. Bouchekima, H. Mahcene, Effect of absorber coating on the performance of a solar still in the region of Ouargla (Algeria), Desalin. Water Treat. 51 (2013) 6490–6497.

[2] R.V. Singh, S. Kumar, M.M. Hasan, M.E. Khana, G.N. Tiwari, Performance of a solar still integrated with evacuated tube collector in natural mode, Desalination 318 (2013) 25–33.

[3] A. Gadgil, Drinking water in developing countries, Annu. Rev. Energy Environ. 23 (1998) 253–286.

[4] G.M. Ayoub, L. Malaeb, P.E. Saikaly, Critical variables in the performance of a productivity-enhanced solar still, Sol. Energ. 98 (2013) 472–484.

[5] A. Hanson, W. Zachritz, K. Stevens, L. Mimbela, R. Polka, L. Cisneros, Distillate water quality of a single-basin solar still: Laboratory and field studies, Sol. Energ. 76 (2004) 635–645.

[6] G. Tiwari, H. Singh, R. Tripathi, Present status of solar distillation, Sol. Energ. 75 (2003) 367–373.

[7] A.E. Silva-Martinez, P. Martinez-Pereda, J.L. Fernandez-Zayas, Dimensionless parameter for assessing a solar still's production, Desalination 281 (2011) 105–110.

[8] V. Velmurugana, K. Srithar, Performance analysis of solar stills based on various factors affecting the productivity—A review, Renew. Sust. Energy Rev. 15 (2011) 1294–1304.

[9] Z.M. Omara, A.E. Kabeel, M.M. Younes, Enhancing the stepped solar still performance using internal reflectors, Desalination 314 (2013) 67–72.

[10] I. A1-Hayek, O.O. Badran, The effect of using different designs of solar stills on water distillation, Desalination 169 (2004) 121–127.

[11] S. Kumar, K.T. Kurmaji, Carbon credit earned by some designs of solar stills, Desalin. Water Treat. 51 (2013) 4699–4708.

[12] K. Zarzoum, K. Zhani, H. Ben Bacha, Improving the design, modeling and simulation in dynamic mode of a solar still, Desalin. Water Treat. 322 (2013) 182–208.

[13] A. Trad, A. Kaab, Effect of orientation on the performance of a symmetric solar still with a double effect solar still (comparison study), Desalination 329 (2013) 68–77.

[14] H. Tanaka, Optimum inclination of still and bottom reflector for tilted wick solar still with flat plate bottom reflector, Desalin. Water Treat. 51 (2013) 6482–6489.

[15] A.J.N. Khalifa, H.A. Ibrahim, Experimental study on the effect of internal and external reflectors on the performance of basin type solar stills at various seasons, Desalin. Water Treat. 27 (2011) 313–318.

[16] H. Tanaka, Experimental study of a basin type solar still with internal and external reflectors in winter, Desalination 249 (2009) 130–134.

[17] H. Tanaka, Y. Nakatake, Increase in distillate productivity by inclining the flat plate external reflector of a tilted wick solar still in winter, Sol. Energy 83 (2009) 785–789.

[18] N. Smakdji, A. Kaabi, B. Lips, Optimization and modeling of a solar still with heat storage, Desalin. Water Treat. 52 (2014) 1761–1769.

[19] O. Ansari, M. Asbik, A. Bah, A. Arbaoui, A. Khmou, Desalination of the brackish water using a solar still with a heat energy storage system, Desalination 324 (2013) 10–20.

[20] G. Singh, S. Kumar, G.N. Tiwari, Design, fabrication and performance evaluation of a hybrid photovoltaic thermal (PVT) double slope active solar still, Desalination 277 (2011) 399–406.

[21] S. Kumar, A. Tiwari, Design, fabrication and performance of a hybrid photovoltaic/thermal (PV/T) active solar still, Energ. Convers. Manage. 51 (2010) 1219–1229.

[22] V. Velmurugan, C.K. Deenadayalan, H. Vinod, K. Srithar, Desalination of effluent using fin type solar still, Energy 33 (2008) 1719–1727.

[23] A. Kianifar, S. Zeinali Heris, O. Mahian, Exergy and economic analysis of a pyramid shaped solar water purification system: Active and passive cases, Energy 38 (2012) 31–36.

[24] A. Madhlopa, C.M. Johnstone, Computation of solar radiation distribution in a solar still with internal and external reflectors, Sol. Energy 85 (2011) 217–233.

[25] J.A. Duffie, W.A. Beckman, Solar Engineering of Thermal Processes, third ed., Wiley Interscience, New York, NY, 2006.

[26] R.V. Dunkle, Solar water distillation: The roof type solar still and a multi effect diffusion still, International developments in heat transfer, in: Proceedings of International Heat transfer Conference, University of Colorado, 5 (1961) 895–902.

[27] P.T. Tsilingiris, Combined heat and mass transfer analyses in solar distillation systems—The restrictive conditions and a validity range investigation, Sol. Energy 86 (2012) 3288–3300.

[28] E.E. Anderson, Fundamentals of Solar Energy Conversion, Addison-Wesley Publishing Company, Reading, MA, 1983.