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Modeling and simulation of the continuous production of an improved solar still coupled with a photovoltaic/thermal solar water heater system

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HIGHLIGHTS

- The proposed system concerns the continuous production of distilled water along the day and night.
- The productivity of active solar still provided (with reflectors), coupled with a (T-SWH) and (PV/T-SWH) has been simulated.
- The stratification model is used to establish the energy balance of a storage tank.
- Subdivision of direct solar radiation over several intervals

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ABSTRACT

This work aims at studying the productivity of a solar active still with a single basin liner and a single slope fitted with two reflectors coupled with a photovoltaic/thermal solar water heater system. The simulation input parameters include climatic conditions concerning the site of Ksar Challala (35.10 N, 2.19 E, Altitude: 800 m) in Algeria, for three typical days, one in each season (winter, spring and summer). The effect of the reflectors on the still daily production is larger during the winter compared with spring and summer. The rise in the production is respectively about 127.06% in winter, 21.78% in spring and 10.1% in summer. Moreover, it is obvious that the still nocturnal production increases when it is coupled with a storage tank either thermal or photovoltaic/thermal out of the sunshine duration. The increase for the still coupled with a thermal storage tank is estimated at about 17.36%, 28.34% and 33.00% respectively for winter, spring and summer. When the still is coupled with a photovoltaic/thermal storage tank, the production increase is very significant and estimated respectively at 47.61%, 137.50% and 131.06% for the winter, spring and summer.

1. Introduction

The shortage of drinking water in most regions of the world is nowadays a major cause for concern. The situation is more crucial in third-world countries because of population explosion and industrial and agricultural development [1]. 97.5% of the worldwide reserves are constituted of salt water and only 2.5% is fresh water [2] which is unequally distributed over the planet [3]. The problem of the drinking water supply can be resolved by the desalination of sea water and/or briny water [4]. Desalination techniques are operational nowadays [1]; nevertheless, their use is often limited to rich countries due to their cost [5]. In the poorest regions, too, where solar radiation is more intense, desalination using solar energy is an even more promising solution [4,6]. Two approaches are in contention; the first consists of the direct use of solar energy to produce water vapor which is condensed after on a cold surface to produce fresh water. The second one consists of capturing solar energy and then converting it into electrical and thermal energy in order to supply thermal and conventional desalination processes [7]. Several types of solar active and passive stills [8] were produced [9,10], however, the improvement of still production is subjected to a large number of researches. [11–16]. One of the techniques used to give a good performance during winter [17,18], consists of the use of reflectors to increase the solar flux absorbed by the basin liner and the brine. The improvement of the running of the solar still during the nocturnal period when solar radiation is absent gives good results on the still production. This can be achieved either by the solar energy stored during the day and used during the night or by providing the heat of the waste matter supplied from different sources on one hand, or by the hot water supplied from any source for a higher production [19–22]. In the paper presented by Voropoulos et al. [32], an experimental study is realized on a solar still coupled with a storage tank. This system can provide continuous distillation during periods when solar

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Nomenclature

Symbols

A	area, m^2
C_p	specific heat, $j \cdot kg^{-1} \cdot K^{-1}$
F_i^c	control function
G	global solar intensity, $W \cdot m^{-2}$
G_{dr}	direct radiation, $W \cdot m^{-2}$
Gr	Grashof number
h_c	heat transfer coefficient by conduction, $W \cdot m^{-1} \cdot K^{-1}$
h_r	heat transfer coefficient by radiation, $W \cdot m^{-2} \cdot K^{-1}$
h_v	heat transfer coefficient by convection, $W \cdot m^{-2} \cdot K^{-1}$
h_{ev}	heat transfer coefficient by evaporation, $W \cdot m^{-2} \cdot K^{-1}$
k	thermal conductivity, $W \cdot m^{-1} \cdot K^{-1}$
K	Boltzmann constant
l_b	length of basin liner, m
l_m	height of external reflector, m
I	current
I_L	photocurrent
I_0	saturation current
M	mass, kg
$\dot{m}$	mass flow rate, $kg \cdot s^{-1}$
n	ideality factor relative the module
Nu	Nusselt number
q, Q	quantity of heat exchanged, $W \cdot m^{-2}$
q_e	electron charge
P_g	saturated partial pressure at glass temperature, $N \cdot m^{-2}$
P_w	saturated partial pressure at water temperature, $N \cdot m^{-2}$
P_n	nocturnal production, $kg \cdot night^{-1}$
Pr	Prandtl number
R_p	shunt resistance
R_s	series resistance
T	temperature, K
t	time, s
v	wind speed, $m \cdot s^{-1}$
V	voltage
W	width of basin liner and external reflector, m

Greek

δ	thickness, m
δT	temperature difference
α	absorbtivity
τ	transmissivity
ε	emissivity
σ	Stefan–Boltzman coefficient, 5.669×10^{-8} $W \cdot m^{-2} \cdot K^{-4}$
θ	angle of the glass cover, deg
ϕ, φ	altitude and azimuth angle of the sun, deg
ρ	mass density, $kg \cdot m^{-3}$
ρ_{ext}, ρ_{int}	reflectance of external and internal reflector
Δ	difference

Subscript

a	ambient temperature
b	basin liner
c	collector
ext	external
ev	evaporation
g	glass cover
gr	ground
i	insulation
int	internal
s	still
sk	sky
st	storage tank
w	water

radiation is low, as it can produce distilled water at a higher temperature. This system can also be used to produce hot sanitary water.

It is in that context that we conducted this work which aims at improving the production of an active solar still. Two methods will be considered, either the use of plane reflectors in order to increase the solar flux during the sunshine period or by the storage of the solar energy in the form of hot water using a storage tank that will supply the still with hot water during the nocturnal period. Thus, we have a continuous production of the distilled water during 24 h. The PV/T-SWH system can be coupled with a field of solar stills in order to increase the production of the distilled water and can be also used to produce domestic hot water.

2. System description

The system studied consists of a conventional still with a single basin liner and a single slope coupled with a hybrid PV/Thermal collector and internal and external reflectors (Fig. 1). The absorber of the solar still is made of galvanized iron because of its simplicity and its low cost. The system is covered with an ordinary glass insulated with a layer of expanded polystyrene. The electric power generated by the hybrid PV/Thermal solar collector enables the active still to operate within a forced circulation mode by the use of a mechanical pump [23,24]. The mode of forced circulation improves the performance of the solar still in comparison to the natural circulation mode; this phenomenon is well explained in the reference [32]. The use of reflectors aims to increase the solar radiation absorbed by the still. The photovoltaic/thermal solar water heater system (Fig. 2) used for supplying the still with hot water during the nocturnal period is made up of a storage tank connected to the hybrid PV/Thermal collector (the electrical power generated by the hybrid collector allows the collector-tank system to operate also in a forced circulation mode). An electrical system constituting of a photovoltaic generator and ohmic heating resistances is used to increase the temperature of the water in the tank (Fig. 2).

3. Mathematical modeling

The model is established by adopting the following assumptions:

- There is no vapor leakage in the still.
- The temperature gradient in the glass cover and the brine of water is negligible.
- The hybrid collector is disconnected from the still and the storage tank out the sunshine period.
- The mode is transitional.
- The storage tank feeds the still during nocturnal period.

3.1. Energy balance

The energy balance of the still and the storage tank are determined by applying the first law of thermodynamics. A detailed mathematical model of the hybrid PV/Thermal collector is presented as [25]

a Still
 - Glass

$$\left(\delta\rho C_p\right)_g \frac{\partial T_g}{\partial t} + q_{v,g-a} + q_{r,g-sk} = q_{ev,g-w} + q_{v,g-w} + q_{r,g-w} + q_{g-ext} + G\alpha_g, \quad (1)$$

where $q_{v,g-a}$, $q_{v,g-w}$, are respectively the quantities of heat exchanged by convection between the glass–ambient and the glass–water systems; $q_{r,g-sk}$, $q_{r,g-w}$, are respectively the quantities of heat exchanged by radiation between the glass–sky and the glass–water systems; $q_{ev,g-w}$, is the quantity of heat exchanged by evaporation between the glass and the water and q_{g-ext}, is