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Theoretical study on the performance of a solar still system integrated with PCM-PV module for sustainable water and power generation

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ABSTRACT

Current paper studies a new solar still system integrated with semitransparent photovoltaic, evacuated tube collectors and phase change materials. Mathematical modeling has been accomplished based on energy/exergy balance equations to investigate the effects of various PCM-PV modules, basin water depth and tube numbers on the system thermal and electrical performance. The system is examined in terms of distilled water production, electricity generation, and energy/exergy efficiencies. Variations of distilled water, system temperature, generated electricity power and energy/exergy outputs and efficiencies over time are presented for various effective parameters. Considering obtained results, while PV type does not affect distilled water, it is the dominant parameter on generated electrical power. Tube number as another important parameter, improves the distilled water production, however, it influences the energy/exergy efficiencies in an inverse way. Presence of PCM, improves the energy efficiency, but has negligible effect on the exergy efficiency. The highest amount of distilled water during a day is calculated for the water basin depth of 0.03 m and 30 tube number with paraffin wax PCM type (4.5503 kg/m^2·day) which is 20.32% more than the case without PCM. Moreover, maximum diurnal energy/exergy efficiencies are reported 17.93% and 6.95% for water depth of 0.03 m and 10 tubes with PCM.

1. Introduction

Freshwater is one of the indispensable elements for domestic usages (e.g. drinking, cooking). It is also an important factor in the development of different industries. Each person needs minimally 20 to 50 l of pure and healthy water per day for urgent usages. Only 2% of the world's water is freshwater and less than 2.53% of this diminutive amount is accessible [1]. So, despite the significant amount of water in the world, there are abundant circumscriptions in availability of freshwater.

Polluted water contains harmful bacteria in which some of them are pathogen. They are mainly responsible for deadly waterborne diseases such as cholera, in remote areas and rural places without availability of clean and safe potable water source. Despite all efforts in developing countries, there are many areas in which healthy drinking water resources are even scarce. Approximately 700 million people still lack freshwater sources for drinking and other urgent usages; nearly half are in sub-Saharan Africa [2].

Major part of the earth surface is covered by water which is mostly impure. Therefore, this insanitary water ought to be pure and potable by specific means. Water desalination is one of the easiest purification means. More than three main approaches of desalination are utilized, known as thermal, electrical, and pressure methods. The thermal distillation, as the oldest method, has been used around thousands of years in which the water is evaporated and then the steam is gathered, leaving the minerals behind. This methodology requires considerable amounts of energy. But in new methods the amount of exploited energy is significantly reduced by using different techniques like low-pressure vessels. Water vapor produced in this method is accumulated and then condensed so as to produce pure and potable water. Major part of bacteria, viruses, minerals, and any chemicals with higher boiling temperature than water are separated from pure water using this process. Therefore, it can be used as safe and clean water for drinking and other urgent usages. Water must be heated in distillation process which needs energy obtained from different power resources. Using conventional sources such as coal, oil and gas are not only costly, but also causes harmful environmental impacts like global warming. By contrast, renewable energy approaches like solar energy do not have these disadvantages [3].

Edalatpour et al. [4] provided a comprehensive review of solar

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Nomenclature

a'	solar collector efficiency coefficient (W/m^2 K)
A_a	aperture area of solar collector (m^2)
A_b	basin area of solar still (m^2)
A_c	PV module area of solar still (m^2)
A_t	circumferential area of each tubular absorber (m^2)
C_{cw}	specific heat capacity of the ETC water (J/kg K)
C_{sw}	specific heat capacity of the basin water (J/kg K)
C_{PCM}	specific heat capacity of PCM (J/kg K)
d_t	evacuated tube inner diameter (m)
dt	small time interval (s)
$\dot{E}_{el}$	electrical energy output of the integrated solar still (W)
$\dot{E}_{el,daily}$	daily electrical energy output of the integrated solar still (W/day)
$\dot{E}_{out}$	overall energy input in integrated solar still (W)
$\dot{E}_{in}$	energy input in integrated solar still (W)
$\dot{E}x_{electrical}$	electrical exergy output in integrated solar still (W)
$\dot{E}x_{in}$	exergy input in integrated solar still (W)
$\dot{E}x_{in,co}$	exergy input in solar still through cover (PV module or glass cover) (W)
$\dot{E}x_{in,ev}$	exergy input in solar still through evacuated tube collector (W)
$\dot{E}x_{out}$	exergy output in integrated solar still (W)
$\dot{E}x_{thermal}$	thermal exergy output in integrated solar still (W)
g	gravitational acceleration (m/s^2)
Gr	Grashof number based on tube inner diameter (−)
h_{ba}	overall heat transfer coefficient from basin to ambient through bottom (W/m^2 K)
h_{bw}	convective heat transfer coefficient from basin liner to water (W/m^2 K)
h_{kg}	heat transfer coefficient of glass cover (W/m^2 K)
h_{go}	overall heat transfer coefficient from inner glass cover to ambient (W/m^2 K)
h_{1w}	total heat transfer coefficient from water to the PV module (W/m^2 K)
h_{cw}	convective heat transfer coefficient from water to the PV module (W/m^2 K)
h_{ew}	evaporative heat transfer coefficient from water to the PV module (W/m^2 K)
h_o	convective-radiative heat transfer coefficient from PV module to ambient (W/m^2 K)
h_{rw}	radiative heat transfer coefficient from water to the PV module (W/m^2 K)
$I_c(t)$	solar radiation over the ETC (W/m^2)
$I_s(t)$	solar radiation over the PV module (W/m^2)
k_b	thermal conductivity of basin material (W/m K)
k_g	thermal conductivity of glass (W/m K)
k_w	thermal conductivity of water (W/m K)
k_{PCM}	thermal conductivity of PCM (W/m K)
k_{ins}	thermal conductivity of insulation (W/m K)
l	length of tube (m)
L	latent heat of vaporization of water (J/kg)
l_b	thickness of basin material (5×10^{-3} m)
L_c	characteristic length
l_g	thickness of glass (m)
l_{PCM}	thickness of PCM (m)
L_{PCM}	heat of fusion (J/kg)
l_{ins}	thickness of insulation (m)
m_{PCM}	mass of PCM (solid) (kg)
$\dot{m}$	natural circulation mass flow rate through an individual tube (kg/s)
$\dot{m}_y$	distillate yields (kg/s·m^2)
M_{sw}	mass of water in the basin (kg)
M_{cw}	mass of water in the ETC (kg)
M_y	daily distillate output of still (kg/m^2·day)
N_c	number of tubes in collector (−)
Nu	Nusselt number (−)
P_c	partial vapor pressure at inner PV module surface (Pa)
P_w	partial vapor pressure at water surface (Pa)
Pr	Prandal number (−)
R_g	transmittivity of glass (−)
T	temperature of fluid (°C)
T_a	ambient temperature (°C)
T_b	basin liner temperature (°C)
T_c	PV module temperature (°C)
T_{cw}	water temperature in ETC (°C)
T_{sw}	water temperature in solar still (°C)
T_{gi}	inner glass surface temperature (°C)
T_{go}	outer glass cover temperature (°C)
T_{PCM}	PCM temperature (°C)
$T_{m,PCM}$	melting point of PCM(°C)
V	wind velocity (m/s)
α_c	absorptivity of PV module (−)
α'_b	fractional solar flux absorbed by basin liner (−)
α'_g	absorptivity of glass (=0.05)
α'_w	fractional solar flux absorbed by water (−)
β	coefficient of thermal expansion (1/K)
β_c	packing factor (dimensionless) (−)
$\beta_{r,m}$	temperature coefficient of the PV module in the standard test condition (−)
ε	exergy efficiency (−)
ε_{eff}	effective emissivity (−)
ε_g	emissivity of glass cover (−)
ε_w	emissivity of water (−)
μ	dynamic viscosity of water (Pa s) (−)
$\eta_{r,m}$	module efficiency in the standard test condition (−)
η_m	module efficiency of the PV module (−)
ν	kinematic viscosity of water (m^2/s)
σ	Stefan Boltzmann constant (5.6697 × 10–8 W/m^2 K^4)
η_o	solar collector efficiency (−)
η_{is}	instant energy efficiency of system

Subscripts

a	ambient air
b	basin
c	solar cell
ov	overall
s	solar still
w	water

distillation systems which mainly operate under two active and passive modes. Passive types are fed with water in ambient temperature but the active one can be fed from several components like solar pound, extra energy (electric or thermal), waste heat and etc. Aybar [5] theoretically modeled and analyzed a passive solar distillation system, which is able to provide distilled and hot water at the same time. Effects of inlet water and solar radiation rate on the system performance are evaluated. The average temperature of hot water was calculated 40 °C, which was maximally reached to 60 °C and then could be used for domestic consumption. In order to continue the process at night time, Rahim [6] proposed a new method to save extra heat energy in horizontal solar desalination stills within the sunshine hours for using at night time. Ebrahim and Elshamarka [7] proposed a passive basin liner, in which an air-cooled condenser alternatively was utilized instead of a glass in conventional distillation system. The system operated at reduced pressure in batch-wise mode. According to their mathematical and