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A novel small dynamic solar thermal desalination plant with a fluid piston converter

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HIGHLIGHTS

- A dynamic solar desalination plant was developed which works cyclically.
- It integrates an evacuated tube solar collector and fluid piston converter.
- Pressure during desalination process varies with frequency of 2–4 Hz.
- The system has a small increase in fresh water yield and provides pumping capacity.
- Mathematical modelling provides accurate description of experimental performance.

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ABSTRACT

An innovative small dynamic water desalination plant was developed and tested under laboratory conditions. The system is a combination of a heat pipe evacuated tube solar collector, conventional condenser and novel fluid piston converter. Saline water is boiled and turned into vapour in the manifold of the solar collector. A small fraction of the solar energy supplied to the plant is used to drive the fluid piston converter. Oscillations of the fluid piston periodically change the volume and pressure in the plant. For the duration of approximately half of the periodic cycle the pressure in the plant drops below the atmospheric level causing flash boiling of saline water in the manifold of the solar collector. Generated vapour is turned into fresh water in the condenser which is surrounded by a cooling jacket with saline water. The flash boiling effect improves the fresh water production capacity of the plant. Additionally, the fluid piston converter drives a pump which provides lifting of saline water from a well and pumps this through the cooling jacket of the condenser to a saline water storage tank. This tank replenishes saline water in the manifold of the solar collector. Experimental investigations demonstrated the saline water self-circulation capability of the plant and increase in the fresh water production compared to the static mode of operation. Experimental data was also used to calibrate the mathematical model of the plant. Comparison of theoretical and experimental information demonstrates that the model accurately predicts the performance of the plant. The proposed novel system with greater fresh water production capacity has a simple design and is easy to manufacture using low cost materials and therefore can be mass deployed for small scale saline water pumping and desalination across different regions with the relatively high solar radiation and shortage in the drinking water supply.

1. Introduction

A range of technologies is deployed to resolve the fresh water deficiency problem, as described by Kalogirou in [1]. Forecast for the number of people to experience the shortage in the drinkable water across 48 countries is 2.8 billion by 2025 [2]. Using the solar energy for the water desalination purpose is considered to be one of the most prospective solutions [3]. The literature review on application of small scale solar desalination plants demonstrates that the majority of research activities have been focused on solar stills. A comparison between the performance of single and double basin solar stills was performed by Al-Karaghuli and Alnaser in [4,5] and it was estimated that the daily average productivity of the double basin solar still is about 40–45% higher than that of a single basin still. El-Sebaii [6] investigated the effect of the mass

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Nomenclature

A	area, m^2
BPE	boiling point elevation, K
C	damping coefficient, N s m^{-1}
C_p, C_v	specific heat at constant pressure and volume, J kg^{-1} K^{-1}
C_{psw}	specific heat of saline water, J kg^{-1} K^{-1}
D	diameter, m
G	solar radiation, W m^{-2}
H	water column height, m
K	gas spring stiffness, N m^{-1}
M	mass, kg
NTU	number of heat transfer units
P	pressure, Pa
Q_r	heat rejected, W
Q_{in}	heat input, W
R	gas constant, J kg K^{-1}
R_b	geometric factor
T	temperature, K
T_{0f}	boiling point of fresh water, K
T_{0sw}	boiling point of saline water, K
S	salt concentration, kg kg^{-1}
U	overall convection heat transfer coefficient, W m^{-2} K^{-1}
V	volume, m^3
X	displacement of fluid column, m
a_o, a_1	constants depending on sky visibility
c_0, c_1, c_2	constants in solar collector efficiency equation
g	gravitational acceleration constant, m s^{-2}
h_g, h_f	enthalpy of vapour and fresh water, J kg^{-1}
h_{fg}	latent heat of vaporization, J kg^{-1}
h_o, h_i	outer and inner convection heat transfer coefficients, W m^{-2} K^{-1}
k_l	thermal conductivity for liquid water, W m^{-1} K^{-1}
k	constant depending on sky visibility
$\dot{m}$	mass flow rate, kg s^{-1}
n	the day of the year

Subscripts

a	air
b	brine
c	condenser
$cool$	cooling water
cp	interface between condenser and fluid piston cylinder
e	evaporator
ec	interface between condenser and evaporator
p	fluid piston cylinder
sw	seawater
v	vapour
1	inner cylinder
2	outer cylinder

Greek symbols

β	slop angle of collector, degrees
γ	isentropic index
ε	effectiveness
η_{SC}	solar collector efficiency
θ	beam angle of incidence, degrees
θ_z	zenith angle, degrees
μ	viscosity, kg m^{-1} s^{-1}
ρ	density, kg m^{-3}
τ_b	atmosphere transmittance for the beam radiation
τ_d	atmosphere transmittance for the diffused radiation

of water in each basin and wind speed, on the productivity in the triple-basin solar still with the use of a numerical model. The basin still with internal and external reflectors was experimentally and theoretically studied by Tanaka [7] and it was reported that deployment of such reflectors increased the daily water productivity by 70–100%. Experimental and theoretical investigations of the basin solar still integrated with a heat pump was performed by Hidouri et al. [8]. The heat pump was used to intensify the condensation process and to enhance the overall efficiency of the solar still. Taamneh and Taamneh [9] experimentally studied the effect of the forced convection in the pyramid solar basin still created by the air fan powered by the photovoltaic panel. It was shown that the forced convection increases the fresh water productivity by 25%.

Tanaka and Nakatake [10] presented a numerical analysis of a tilted wick solar still with a vertical flat external reflector used to enhance the radiation flux into the still. The results showed that the productivity was increased by about 9% compared to a plain wick still. In [11] Tanaka and Nakatake investigated the tilted wick solar still with the vertical flat reflector equipped with a manual azimuth tracking system. It was stated that such the technique improved the fresh water production by approximately 41%. The same authors in [12] examined the tilted wick solar still with the inclined flat reflector and observed the improvement in the productivity by 15–27% compared to the case with the vertical reflector. A solar still with concave wick was described by Kabeel in [13]. The concave surface of the still and pyramid shaped cover increased the evaporation and condensation areas, respectively, which resulted in fresh water production enhancement. Mahdi et al. [14] experimentally studied the performance of the tilted wick solar still using charcoal as an absorber. Tanaka and Nakatake [15] described the multi-effect diffusion solar still which included a flat mirror reflector. The experiments demonstrated the productivity of such the design being significantly greater than that of the conventional single effect stills. Numerical simulation and outdoor experiment results of the vertical diffusion solar still for different inclination angles of the reflector and orientations of the still were described in [16,17]. Tanaka presented in [18] results of the experimental study on the effect of a number of partitions in the vertical multiple effect diffusion solar still with a flat reflector.

A numerical and experimental investigation of the tubular type solar still for desert irrigation purposes was described by Murase et al. in [19,20]. Ahsan et al. presented in [21–23] results of study on the tubular solar still, including description of the mathematical model which takes into account properties of air in the still.

Kumar and Tiwari described in [24] results of the experimental and theoretical studies on the hybrid photovoltaic/flat plate collector (PV/T), which had been used as a part of the active solar still. They also determined the magnitude of the internal heat transfer coefficient which defines the intensity of the saline water evaporation process. In [25] Kumar et al. developed the empirical correlation for calculation of the temperature of the cover for the active solar still. Singh et al. [26] investigated the performance of the double slop basin solar still with the hybrid PV/T collector.

Investigations of the effect of design parameters of the multi-effect solar still coupled with the evacuated tube solar collector were performed by Shatat and Mahkamov in [27]. Kabeel et al. presented in [28] study results for the steeped basin solar still coupled with the evacuated tube solar collector. Gude et al. described in [29,30] research results for the solar thermal