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Performance evaluation of a continuous flow inclined solar still desalination system

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ABSTRACT

In the present work, theoretical study of the performance evaluation of a continuous water flow inclined solar still desalination system is performed. Three models are studied for inclined solar still desalination system with and without water close loop. The effects of the water mass, water film thickness, water film velocity and air wind velocity on the performance of the three models are studied. The results show that the inclined solar still with a makeup water is superior in productivity (57.2% improvement) compared with a conventional basin-type solar still. Also, the application of inclined solar still with open water loop is recommended when combined with other still desalination system due to high water temperature output. The inclined solar still with a makeup (Model 3) gives the highest performance while Model 1 gives the lowest performance. Finally, the water film thickness, and velocity as well as wind velocity plays important roles in improving the still productivity and efficiency.

1. Introduction

Although water covers approximately 70% of the earth's surface, supplies of potable water are one of the major problems in many countries. This is because most of the water reservoirs are saline or has harmful bacteria. The use of solar stills as a cheap and simple method for providing potable water and it is safe outcome on the environment is the major attraction points to research interests. The weak points for using solar stills for distillation of sea or salt water are its low efficiency and production rate as compared to the conventional systems.

The level of water on the absorber surface had been shown to be an important factor affecting the productivity [1]. It was reported that, the solar still performance was increased with thinner water films. This can be achieved by inclined and stepped absorber surfaces. Stills with inclined absorber surfaces and open loop continuous water flow were reported to have significantly higher productivity compared with basin-type stills.

To enhance the performance of the solar still system, Aybar et al. [2], Aybar [3], and Agboola and Egelioglu [4] studied the effect of varying some specific parameters of the first design of inclined solar still. Omara et al. [5] improved the performance of a modified stepped solar still by using an internal and external reflectors. It was found experimentally that the productivity of the modified stepped solar still with internal and external reflectors was higher than that for conventional still approximately by 125%.

The integration of different depths of trays of the fin and sponge at the basin of the still was studied by Velmurugan et al. [6–8]. The results showed that, the average daily productivity of stepped solar still was found higher than that the single basin solar still when used the fin and sponge type. The effect of varying both depth and width of the trays on the performance of the stepped still was studied theoretically and experimentally by Kabeel et al. [9]. They reported that the maximum productivity of stepped still was about 57.3% higher than that of the conventional still at a tray depth 5 mm and width 120 mm. Radhwan [10], El-Sebaii et al. [11], and Dashtban and Tabrizi [12] studied the effect of using a phase change material in stepped solar still efficiency. The results showed that the modified still was efficient for produced water during the lack of sunlight especially at night. The performance of a stepped solar still using a spray seawater system was studied by El-Zahaby et al. [13,14]. The results indicated that, the daily productivity and efficiency of the modified stepped still was higher than that for conventional still.

Besides, Awad and El-Agouz [15] studied experimentally stepped solar still open loop continuous water flow using humidification–dehumidification processes to improve the solar still performance. The results showed that by increasing the air flow rate, the solar still performance was increased.

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Nomenclature

A	area (m^2)
C	specific heat (J/kg °C)
h_{cga}	convection heat transfer coefficient between glass cover and atmosphere (W/m^2 °C)
h_{cpw}	convection heat transfer coefficient between absorber plate and saline water (W/m^2 °C)
h_{fg}	latent heat of vaporization (J/kg)
I	solar intensity normal to glass cover (W/m^2)
k	thermal conductivity (W/m °C)
L	characteristic length (m)
M	mass (kg)
M_w	hourly productivity (kg/hr)
m_w	water mass (kg)
$\dot{m}$	mass flow rate (kg/s)
Nu_{cpw}	average Nusselt number between absorber plate and saline water
Pr	saline water Prantel number (–)
P_{sat}	water vapor saturated pressure (Pa)
Q_{cga}	convection heat transfer from glass cover to ambient (W)
Q_{cond}	condensation heat transfer rate (W)
Q_{cpw}	heat transfer from absorber plate and saline water (W)
Q_{evap}	evaporation heat transfer rate (W)
Q_{loss}	heat loss from absorber plate to ambient (W)
Q_{rga}	radiation heat transfer from glass cover to ambient (W)
Q_{rwg}	radiation heat transfer from saline water to glass cover (W)
Q_w	saline water gained energy (W)
R	gas constant (kJ/kg K)
Re	saline water Reynolds number (–)
T	temperature (°C)
t	time (s)
U	saline water velocity (m/s)
U_b	overall heat transfer coefficient (W/m^2 K)
V	volume (m^3)
v_a	air velocity (m/s)
w	width of solar still (m)

Greek letters

ΔT	air–vapor mixture to saline water temperature difference (°C)
α	absorption coefficient
ε	emissivity coefficient
μ	dynamic viscosity (kg/m s)
ρ	density (kg/m^3)
σ	Stefan–Boltzmann constant ($W/m^2\ K^4$)
τ	transmissivity coefficient (–)
φ	air relative humidity ($kg_w/kg_{dry\ air}$)

Subscripts

a	air
am	ambient
cond	condensation
evap	evaporated
ex	exit
g	glass cover
in	inlet
m	air–vapor mixture
P	absorber plate
sky	sky
w	saline water
v	water vapor

Egelioglu et al. [16] presented experimental results of four different configurations of inclined solar water desalination system with spray jets and open loop continuous water flow. The effect of the spray jets on the economic and thermal performance of the systems was investigated. The results showed that the jets variation, wick material, and solar radiation were the main factors that influence the desalination system performance.

El-Agouz [17] presented experimentally performance of stepped solar still with continuous water circulation using a storage tank for sea and salt water in order to enhance the productivity. It was found that the daily efficiency for modified stepped still was higher than that for conventional still approximately by 20%.

The literature review on inclined or stepped solar stills shows that there are extensive works on the system with an open loop continuous water flow. There are shortage in theoretical works in solar desalination system that involves the use of a closed loop continuous water flow with and without makeup water. In the present work, the change of air relative humidity inside a solar still due to the difference between the amounts of evaporated to condense water vapor is taken into account. A novel theoretical study of the performance evaluation of a continuous water flow inclined solar still desalination system is obtained. Three models are studied, evaluated and compared with the conventional solar still (CSS). The first model is an open loop continuous water flow inclined solar still (Model 1). The second model is a closed loop continuous water flow inclined solar still without a makeup water (Model 2). The third model is a closed loop continuous water flow inclined solar still with a makeup water (Model 3). The effect of the water mass, water film thickness, water film velocity and air wind velocity on the performance of three models are studied.

2. Mathematical model

In the present study, three continuous flow inclined solar stills and conventional solar still are studied as shown in Fig. 1. In the Model 1, Fig. 1(b), the saline water is in an open loop, i.e. the exit saline water is pumped to a drain. In the Models 2 and 3, Fig. 1(c), the saline water is in a closed loop. Saline water is pumped from a mixing storage tank (MST) to the top of the absorber plate through CV (control valve) and FM (flow meter). After then the saline water is flowing with film thicknesses on absorber. The solar energy evaporates part of water which is then condensed on the glass cover. Saline water remaining at the bottom of the absorber plate is directed to the thermal storage tank. No makeup water is added to the mixing storage tank in Model 2, i.e. the amount of saline water in the tank is decreased with time (variable level storage tank). A makeup water is added to the mixing storage tank in Model 3. The amount of this makeup saline water is equal to the amount of evaporated water in the still i.e. the amount of saline water in the tank is constant during the day (constant level storage tank).

2.1. Continuous flow inclined solar still

The energy balance for a continuous flow inclined solar still may be applied for the basin (absorber plate), saline water, and glass cover. The following assumptions are considered for all studied solar still energy equations:

- Glass cover conduction resistance is neglected (the glass cover is assumed to be thin).
- The solar still is vapor leakage proof.