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Thermodynamic investigation of a semi-open air, humidification dehumidification desalination system using air and water heaters

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ABSTRACT

In this paper, a semi-open air, open water humidification dehumidification (HDH) desalination system is proposed and studied. It is shown that for both water- and air-heated systems, when the top temperature of the system is fixed, this presented method for air circulation can enhance the performance of the system. Analyzing other parameters reveals that the impact of ambient temperature is more important than that of the ambient relative humidity on system performance; therefore, HDH is efficient for both dry and humid climates. Also, when the ambient temperature is high, closed air loop has a higher performance. Moreover, the proposed system is studied with a dual heating method, in which both water and air were heated using a wide range of heat rate ratio. The results show that the system will have the maximum performance when the heat rate ratio approximately equals one. In case only one of the streams is heated, if the energy intake is low, water heating is a better solution for an efficient system, but when the heat input is high, air heating is more effective. Finally, an entropy generation analysis of the proposed configuration and heating method is conducted. It is suggested that the exergy efficiency can be used for optimization.

1. Introduction

The shortage of fresh water is escalating daily due to population growth, industrialization and urbanization. Although an abundant quantity of water is available in nature, only 1% of it is potable. Desalination of sea water is an important and essential solution for this problem since the oceans are an unlimited source of water. The typical desalination methods such as multi-stage flash (MSF), multi-effect desalination (MED), vapor compression (VC), and reverse osmosis (RO) are usually large-scale technologies. However, they can be used for small-scale needs too specially reverse osmosis desalination which is a low to high capacity desalination technology. These technologies cannot be used in remote regions, where maintenance equipment is restricted and inadequate, and conventional energy is not available or costly. Additionally, conventional sources of energy are environmentally harmful. Consequently, the renewable energy resources provide an alternative source to cover the energy needed for desalination processes. All the mentioned technologies can utilize solar energy as their power source [1]. One of the solar desalination technologies is humidification-dehumidification (HDH) desalination. HDH is a method for remote, off-grid, decentralized and arid areas because of its low capital cost, simple design, low maintenance, cost-free energy and environment-friendly design. In fact, HDH is a small-scale desalination technology that imitates nature's water cycle and operates at atmospheric pressure.

Dai et al. [2,3]studied an HDH desalination system using a solar flat collector for water heating with open air circulation. They concluded that the mass flow rate of process air and the temperature and mass flow rate of the feed water affected the system performance. Mohamed and El-Minshawy [4] investigated an open air HDH desalination system that used a parabolic collector in order to heat up water and air inlet to the humidifier. They observed that the amount of fresh water productivity depends on the solar radiation and solar time (daytime); then, by increasing the day time, the productivity increases to a maximum value and then decreases. Therefore, the maximum fresh water productivity by this type of HDH is expected in summer season because of high direct solar radiation and long solar time. Yuan et al. [5]studied an HDH with open air circulation which preheated air inlet and heated up water inlet to the humidifier and had an individual system for condensing moisture in the air. They observed that under the same cooling conditions, raising the temperature and relative humidity of outlet air from the humidifier improved fresh water production of the unit. Yildirim et al. [6]studied an open air HDH system with a flat plate solar water heater and a flat plate double pass solar air heater. In their theoretical study, they analyzed how some operational and design variables influence the clean water production rate. Their research

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Nomenclature

c_p	specific heat capacity at constant pressure, (kJ/kg. K)
F	the ratio of mass flow rate of dry air that returned from the output of dehumidifier to the system, to the total mass flow rate of dry air circulating inside the system
g	Gibbs free energy, (kJ/kg)
GOR	gained output ratio
h	specific enthalpy, (kJ/kg)
h_{fg}	latent heat of vaporization, (kJ/kg)
HCR	heat capacity ratio
$\dot{m}$	mass flow rate, (kg/s)
m_r	mass flow rate ratio
P	absolute pressure, (Pa)
$\dot{Q}_{in}$	input heat rate, (kW)
R	universal gas constant, (kJ/kmol. K)
s	specific entropy, (kJ/kg. K)
$\dot{S}_{gen}$	entropy generation rate, (kJ/K. s)
T	temperature, (K)
$\dot{W}_{least}$	least work of separation, (kW)

Greek symbols

ε	Effectiveness
η_{II}	exergy efficiency
$\dot{\Xi}$	exergy rate, (kW)
ξ	specific exergy, (kJ/kg)
ϕ	relative humidity
ω	humidity ratio, (kg_w/kg_a)
$\bar{\omega}$	Humidity ratio, (mol_w/mol_a)

Subscripts

0	dead state (ambient)
a	air
b	brine
c	cold stream
D	dehumidifier
da	dry air
f	saturated liquid
g	saturated vapor
h	hot stream
H	humidifier
HT	heater
in	inlet
L	liquid phase
mix	mixture
ma	moisture air
out	outlet
p	pure water
sat	saturation
sw	sea water
trans	transferred
w	water
WB	wet bulb

contained distinct configurations of the system including water-heated, air-heated and dual heating under the weather conditions of Antalya, Turkey. It was shown that clean water production was better affected by water heating rather than air heating. Moreover, the system production positively depended on mass flow rate of air and feed water. Nonetheless, there existed a specific value of air mass flow rate for which clean water production was maximized. Rajaseenivasan and Srithar [7] investigated experimentally an open air HDH integrated with a dual purpose solar collector which was used to heat water and air at the same time. They used convey and convex shape turbulators in air field and both the heated flows were transferred to the humidifier. They conducted that the flow rate of air, hot water in the humidifier and cold water in the dehumidifier enhance the distillation capacity of the system.

Al-Halaj et al. [8]investigated a water-heated HDH system with forced and natural closed air circulation. They observed that water flow rate is a very impressive parameter on water production up to an optimum value. Also, they suggested that when the top temperature of the system is high, using natural air circulation, and when the top temperature is low, forced air circulation are appropriate methods of air circulating. Fath and Gazhy [9] investigated a closed-air HDH with air heating system. They observed that an enhancement of solar intensity and ambient temperature positively affect system productivity and the dehumidifier effectiveness has an inconsequential effect on clean water productivity. Nafey et al. [10,11]studied a closed-air HDH system with an air and water heater. The system had a water-cooled exchanger as the dehumidifier which used individual water circulation for cooling. Their experimental results were in good agreement with their numerical work and they indicated that the inlet saline water and air temperatures to the humidifier influence the productivity of the system. Furthermore, air flow rate, cooling water flow rate running through the dehumidifier, and solar intensity had an important role in productivity.

Orfi et al. [12]examined a theoretical water and air heating HDH desalination system with closed and open air circulation in Tunisia. They showed the ratio between the saline water and the air mass flow rates affect the daily fresh water production, and under the same conditions for the systems, water production of the open air system is more than the closed one except in November and December. Also, comparison of annual performances for the mentioned configurations showed that the open-air system gives a better fresh water production.

Narayan et al. [13,14]conducted a theoretical cycle analysis over various solar-driven HDH systems including water-heated and air-heated closed air, open water (CAOW) and water-heated closed water, open air (CWOA)types. They defined modified heat capacity ratio (HCR) for heat and mass exchange devices which is the rate of maximum possible enthalpy change of the cold stream to that of hot stream. They found the irreversibility of heat and mass exchanger devices can be minimized for a given fixed inlet condition and energy effectiveness according to the value of HCR which means the performance of heat and mass exchanger can be improved by bringing the HCR value closer to one. Based on this idea they proposed novel methods such as novel air-heated, multi-extraction, multi-pressure and thermal vapor compression cycle for the improvement of the system performance. They showed that the novel air-heated system in which air was heated before entering the dehumidifier is much more efficient than usual air heating (i.e. air heated before entering the humidifier). Al-Sulaiman et al. [15] thermodynamically investigated an open air, open water (OAOW) HDH system integrated with a parabolic trough solar collector for air heating. They considered two configurations of the system; first, the air heater was located before the humidifier and second, before the dehumidifier. They revealed that the second configuration had a much better performance and the gained output ratio (GOR) of 4.7 on average whereas GOR of the first configuration was about 1.5. Then, they concluded that heating air before it enters the dehumidifier was more advantageous and productive of more clean water than the conventional methods of air heating before the humidifier. Therefore, in this paper air was just heated before dehumidifier.

Mistry et al. [16] studied the humidification-dehumidification (HD) desalination systems thermodynamically, considering the energy conservation equation and entropy generation of each component and the