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Performance analysis of an air-heated humidification–dehumidification desalination plant powered by low grade waste heat

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ABSTRACT

Humidification dehumidification desalination system has shown advantages to satisfy small scale freshwater demand. In this paper, an air-heated humidification dehumidification desalination system powered by low grade waste heat, coupled with plate heat exchangers, is constituted. Working mechanisms of the air-heated HDH desalination system are revealed, and performance for both the humidification dehumidification desalination unit and the plate heat exchangers is obtained and analyzed based on the established mathematical models. Entropy generation of both the components and the whole humidification dehumidification desalination system is calculated to judge the feasibility of the system cases and demonstrate the energy loss. Simulation results show that despite the top value of the gained-output-ratio, 3.51, at the balance condition of the dehumidifier with a negative specific entropy generation of the dehumidifier, the actual maximum value is 3.04 when the mass flow rate ratio between the seawater and the dry air is $\dot{m}_{sw}/\dot{m}_{da} = 1.28$. Based on the elevation of the heat transfer rate and the descendant trend of the heat transfer coefficient, the heat transfer area of the plate heat exchangers rises from $A = 5.25\ m^2$ to $A = 15.90\ m^2$. Furthermore, it is summarized that the pressure drop of the plate heat exchangers will result in a very limited adverse influence on the energy utilization efficiency of the whole humidification dehumidification desalination system.

1. Introduction

In view of the serious water shortage all over the world, extensive attentions were attracted to separate freshwater from the large amount of seawater. As a result, different types of desalination methods were suggested and put into reality in the past years. Janajreh [1] proposed a method of multi-stage flash (MSF) to produce freshwater, and vapor flow and pressure drop across the demister desalination plant were numerically simulated. Maraver [2] gave out a configuration of a polygeneration system for power and water, which was obtained with a multi-effect distillation (MED) desalination system. Samake proposed a multi-effect thermal vapor-compression (METVC) desalination systems, and the correspond performance was simulated [3], and mechanical vapor compression (MVC) powered with a compressor was also applied to produce freshwater [4]. In spite of the thermal method, reverse osmosis (RO) was another type of desalination method to produce water [5]. However, for the sake of maintenance and efficiency of such large scale desalination stations, a huge amount of energy consumption, fossil fuel or electricity, is needed to produce freshwater.

Both the theory and actual experience showed that the desalination systems listed above were not appropriate for the small scale requirements of freshwater due to the low efficiency of energy utilization [6]. Hence, a special desalination method was urgent to satisfy the freshwater supply for the small scale demand. Narayan [7] proposed an effective desalination method, in which humidification and dehumidification formed the main thermal processes, and the corresponding performance was analyzed. Owing to the superiority of the HDH desalination system, extensive investigations have focused on the system constitution and the relevant performance analysis in the past few years.

Due to the deficient analysis for the humidification dehumidification (HDH) desalination systems, Narayan [8] numerically simulated the performance of various HDH desalination cycles, including the water-heated and air-heated types, and the corresponding performance of these systems, such as

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Nomenclature

Roman symbols

A	heat transfer surface area (m^2)
b	channel height of the PHEs (mm)
c_p	specific heat ($J\ kg^{-1}\ K^{-1}$)
D_h	hydraulic diameter (m)
h	convective heat transfer coefficient ($W\ m^2\ K^{-1}$); enthalpy ($kJ\ kg^{-1}$)
L	plate length (mm)
$\dot{m}$	mass flow rate ($kg\ s^{-1}$)
N	plate number; power (W)
Nu	Nusselt number
p	pressure (MPa); wet perimeter (m)
Q_r	heat transfer rate (kW)
P_r	Prandtl number
Re	Reynolds number
S	concentration of seawater ($g\ kg^{-1}$)
S_p	area of the plate (mm^2)
ΔT_m	log mean temperature difference (K)
T	temperature (K)
K	overall coefficient ($W\ m^{-2}\ K^{-1}$)
v	velocity (ms^{-1})
w	humidity ratio ($g\ kg^{-1}$)
W	channel width (m)

Greek letters

β	plate chevron angle (°)
δ	plate thickness (m)
φ	coefficient of area expansion
ρ	density ($kg\ m^{-3}$)
μ	dynamic viscosity ($kg\ m^{-1}\ s^{-1}$)
ε	effectiveness of the humidifier and dehumidifier
ϕ	relative humidity
λ	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
γ	latent heat ($kJ\ kg^{-1}$)
η	efficiency

Subscripts

a	air
b	brine; blower
ch	channel
d	dehumidifier
da	dry air
e	exhaust
fw	freshwater
h	humidifier
i	inlet
max	maximum
min	minimum
o	outlet
p	plate
q	qualitative
s	saturation
sw	seawater
t	turbulence; total
w	wall

Acronyms

HDH	humidification dehumidification
PHEs	plate heat exchangers
GOR	gained-output-ratio
HCR	heat capacity ratio
MED	multi-effect distillation
MGOR	modified gained-output-ratio
MSF	multi-stage flash
MVC	mechanical vapor compression
PTSC	parabolic trough solar collector
TVC	thermal vapor compression
RO	reverse osmosis

gained-output-ratio (GOR), exit humidity of the humidifier, were calculated. Furthermore, the corresponding improvements were presented and verified by comparisons between the original and suggested novel desalination systems.

Based on the huge potential of the solar energy, it was also used to drive the HDH desalination system both for the seawater and air side, and such systems are especially applicable for the area with deficient infrastructure and skilled manpower [9]. The performance of a HDH desalination system, powered by solar energy both for the water and air heater, for various operating and design parameters, such as air and cooling water mass flow rate, air heater tilt angle, air heater tilt angle, under climatological conditions of Antalya, Turkey was investigated by Yildirm and Solmus [10]. Based on the fourth order R–K method, the related mathematical models and governing conservation equations were numerically solved, and daily and annual freshwater yields were obtained at different working conditions of such a desalination system.

Al-Sulaiman [11] suggested the parabolic trough solar collector (PTSC) to heat the humid air in the open-air, open-water HDH desalination system. The related thermodynamic performance of two different specific schemes were calculated and compared, acquiring the corresponding influences on the performance of the whole HDH desalination system. It was found that PTSC was well suited for air heated HDH systems in the high radiation locations, and the scheme with the air heater located between the humidifier and the dehumidifier had a better energy efficiency and a higher freshwater production.

A theoretical simulation model of a water-heated solar desalination unit was also suggested by Hamed [12], and energy equations of each component within such unit considered were solved to evaluate the relevant performance as well as the freshwater yield. Two periods, first one from 9:00 am to 5:00 pm and second one from 1:00 pm to 5:00 pm, were designated to calculate the freshwater production of the proposed system. The final simulated results told that the highest freshwater production was found in the second period. Furthermore, in order to validate the accuracy of the theoretical results for the proposed desalination system, the relevant experimental platform was built to test the heat and mass transfer process within the system, and a good agreement of the comparison between experimental and theoretical results, including the temperature at the inlet and outlet of the condenser and the productivity of the system, presented the significance of the new water-heated solar desalination system.

Chiranjeevi [13] proposed a two stage HDH system integrated the cooling plant to augment the desalination production. Experimental and simulation studies were simultaneously investigated based on the developed pilot plant, in which a solar water heater is used to heat the saline water for the demand of two humidifiers and two air preheaters. It was found that freshwater yield is not satisfactory with a lower water temperature in the first stage while