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Parametric analysis of a humidification dehumidification desalination system using a direct-contact dehumidifier

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ABSTRACT

Humidification dehumidification (HDH) technology is efficient to evaporate freshwater from seawater or brackish water. In this paper, a water-heated HDH desalination system to recover waste heat through plate heat exchangers (PHEs) is proposed, and heat and mass coupled processes are both applied in the humidifier and dehumidifier. In view of the mathematical models based on energy equilibrium and entropy generation, characteristics of the advised desalination system at different appointed key parameters are calculated and analyzed. Surface areas involved in the PHEs, which contain the low grade heat collector (LGHC) and the hot water recuperator (HWR), are obtained. The simulation results show that the modified heat capacity ratio (HCR) of the humidifier, HCR_h, is always at $HCR_h>1$ for the prescribed operation conditions, while the balance condition of the dehumidifier, $HCR_d = 1$, is available, which is significant for the performance of the HDH desalination system. A maximum value of GOR, $GOR = 2.01$, is attained corresponding to the minimum irreversible loss of the whole desalination system. Furthermore, in consideration both of the heat and mass transfer area as well as the water production, the unit cost is acquired as $C_{u,c} = 26.94$ ¥ t-1h and Cu,t = 68.13 ¥ t-1h, which indicates a great superiority of the HDH desalination system using a direct-contact dehumidifier compared with the traditional type.

1. Introduction

As a result of the serious shortage of the freshwater resources, water production methods as well as the corresponding desalination devices have drawn more and more attentions all over the world. Kinds of desalination patterns, which can be divided into the thermal and membrane type, were proposed and put into applications. At the aspect of thermal desalination method, relevant large scale desalination plants based on multi-stage flash (MSF), thermal vapor compression (TVR), multi-effect evaporator (MEE), mechanical vapor compression (MVC), were constructed [1–3]. However, such desalination plants consumed a huge amount of thermal energy to complete the freshwater production, and they were not suitable for the small scale applications due to a low energy utilization efficiency. For the membrane based desalination system [4,5], continuous supply of mechanical energy produced by electricity should be available to drive the power machinery.

However, small scale requirements of water production also exist for many occasions, such as the watercraft and island, and a promising desalination method with humidification dehumidification technology was proposed [6,7]. Extensive investigations have been focused on such desalination systems all over the world.

Performance of various HDH desalination cycles were numerically simulated by Narayan [8], and then the novel high-performance desalination cycles to improve the original desalination systems were first proposed, containing multi-pressure, thermal vapor compression and multi-extraction. It was verified that the desalination systems with these proposed novel cycles will show powerful superiority compared to the original HDH systems. Chehayeb [9] proposed a fixed-size HDH system, which consisted of a packed-bed humidifier and a multi-tray bubble column dehumidifier, and the effect of the mass flow rate ratio on the entropy generation and the driving forces for heat and mass transfer were investigated. In view of a generalized energy effectiveness for heat and mass transfer devices, an air extraction/injection was also

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Nomenclature

Roman symbols

a	specific area (m^2m^{-3})
A	heat transfer surface area (m^2)
b	channel height of the plate heat exchangers (mm)
C	cost (¥)
c_p	specific heat ($Jkg^{-1}K^{-1}$)
d	humidity ratio (gkg^{-1})
D_h	hydraulic diameter (mm)
D_{HWR}	distance along the HWR (mm)
D_{LGHC}	distance along the LGHC (mm)
h	convective heat transfer coefficient (Wm^2K^{-1}); enthalpy ($kJkg^{-1}$)
H	height (m)
k	mass transfer coefficient ($kgm^{-2}s^{-1}$)
m	mass flow rate (kgs^{-1})
Nu	Nusselt number
p	pressure (MPa); wet perimeter (m)
Q	heat load (kW)
P_r	Prandtl number
Re	Reynolds number
s	specific entropy ($kJkg^{-1}K^{-1}$)
S	concentration of seawater (gkg^{-1}); entropy rate ($kJs^{-1}K^{-1}$)
S_p	plate area (mm^2)
ΔT_m	log mean temperature difference (K)
T	temperature (K)
U	overall heat transfer coefficient ($Wm^{-2}K^{-1}$)
v	velocity (ms^{-1})
V	volume (m^3)
W	channel width (m)

Greek letters

β	plate chevron angle (°)
δ	plate thickness (mm)
ρ	density (kgm^{-3})
μ	dynamic viscosity($kgm^{-1}s^{-1}$)
ε	effectiveness of the humidifier and dehumidifier
ϕ	relative humidity
λ	thermal conductivity ($Wm^{-1}K^{-1}$)
γ	latent heat ($kJkg^{-1}$)

Subscripts

a	air
b	brine
c	cold; current
ch	channel
d	dehumidifier
da	dry air
e	exhaust
g	generation
h	hot; humidifier
HWR	hot water recuperator
i	inlet
$LGHC$	low grade heat collector
LH	low grade heat collector and hot water recuperator
m	maximum
o	outlet
p	plate
pw	pure water
$\underline{s}$	saturation
sw	seawater
t	turbulence; total; traditional
u	unit
w	water, wet

applied.

Renewable energy, especially solar energy, was usually applied to power the HDH desalination system, and it is suited for regions which are short of the infrastructure and skilled manpower [10]. A mathematical simulation model to assess the related performance as well as the productivity of a solar desalination unit was advised by Hamed [11]. Freshwater production of the proposed system was calculated in two periods: the first one from 9 a.m. to 17 p.m., the second one from 13 p.m. to 17 p.m. The final obtained results showed that the highest freshwater production arised in the second period. Moreover, a relevant experimental system was also built to test the heat and mass transfer characteristics in the desalination system. Finally, a comparison between the experimental and theoretical results agreed very well, which validated the proposed theoretical model applied in the solar HDH desalination system.

Kabeel [12] accomplished an experimental investigation of a desalination system based on the HDH method with open-water and closed-air cycles powered by an evacuated solar water heater. Performance of the desalination system with natural and forced air circulation are simulated, respectively. Results from the proposed design were compared with that of the conventional type, and the comparison indicated that the proposed design gives a higher performance.

A parabolic trough solar collector (PTSC) was advised to be integrated into the open-air, open-water, air-heated HDH system by Al-Sulaiman [13], and the corresponding thermodynamic performance was analyzed. The influences from the configurations of the solar air heater on the performance of the whole HDH desalination system were discussed. It was revealed that PTSCs are well suited for air-heated HDH systems for high radiation locations, and the HDH configuration with the air heater placed between the humidifier and the dehumidifier has a better performance and a higher productivity.

Mistry [14] achieved the analysis of entropy generation for a closed-air open-water HDH desalination system with both air heater and water heater. The equations both of the entropy generation and exergetic were established. Based on the simulation results, it was proposed that entropy generation minimization analysis is necessary and helpful to identify the key components and operating conditions, which should be considered while designing the HDH desalination systems.

In the involved HDH desalination system above, surface heat exchanger were always used as the dehumidifier, and significant pressure drop, corrosion and blocking resulting from the seawater increased the operation cost and reduced the lifetime of the desalination system [15,16]. Niroomand [17] introduced a kind of direct contact dehumidifier into the HDH desalination system, in which humid air is dehumidified by spraying cold water into the hot humid air flow. Sensitive analysis of the thermal parameters containing air flow rate, conditions of inlet cold and hot water on the performance of the desalination system were studied. It was verified that such direct contact dehumidifier was a good choice to improve the general application of the HDH desalination system.

From the previous literature survey, it is found that HDH