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Thermo-economic analysis of a water-heated humidification-dehumidification desalination system with waste heat recovery

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ABSTRACT

Humidification dehumidification (HDH) processes have been proved to be efficient for producing freshwater from seawater or brackish water. In this paper, an HDH desalination system, in which the seawater is appointed to recover the waste heat, is suggested. Based on the principles of mass and energy conservation, mathematical models for all the contained components as well as the entire desalination system, are built, and then the relevant thermo-economic analysis is also accomplished. The simulation results show that peak values of water production with $m_w = 99.05\,\mathrm{kg\,h^{-1}}$ and gained-output-ratio (GOR) with $GOR = 1.51$ are obtained when the balance condition of the dehumidifier appears at the design conditions, while a bottom value of unit cost of water production (UCWP) is found as $UCWP = 37.68\$\,\mathrm{kg^{-1}\,h}$ at the case of $m_{da} = 0.14\,\mathrm{kg\,s^{-1}}$. Hence, the great advantages at the aspect of cost for unit water production compared to the solar drive type is validated. It is also found that reducing the seawater spraying temperature and elevating the humidification effectiveness are beneficial to raise the relevant thermodynamic and economic performance of the desalination system. With respect to the variation for dehumidification effectiveness, the peak value of GOR rises from $GOR = 1.28$ at $\varepsilon_d = 0.8$ to $GOR = 1.85$ at $\varepsilon_d = 0.9$, while a peak value of UCWP is obtained as $UCWP = 50.12\$\,\mathrm{kg^{-1}\,h}$ due to the substantial increase of the heat transfer area for the dehumidifier.

1. Introduction

Due to the serious environment problems from the industrial pollution, water shortage situation is more and more serious all over the world. Therefore, different types of desalination methods to produce fresh water, were considered and realized in the past years [1,2]. However, the generally utilized desalination systems, divided into the thermal and membrane version [3,4], are applied for large scale water requirements, always with shortcomings of complicated structure, high energy input and investment. Simultaneously, small scale water requirements are also ubiquitous in the people's life and industry, and it is urgent to be explored. Thereinto, a promising thermal desalination method, which simulates the natural humidification dehumidification processes, was advised and investigated extensively. [5–7], and extensive investigations have been accomplished on such method in the field of desalination.

Thermodynamic performance of such HDH desalination system was one of the research focus. For different HDH desalination systems, Narayan [8,9] achieved the performance simulation based on the platform of Engineering Equation Solver (EES). Based on the sensitive analysis for different thermal parameters, specific methods were introduce to improve the original desalination configurations, such as variable pressure, thermal vapor compression and intermediate extraction, and they were found to be efficient to update the efficiency of the desalination process. A fixed scale HDH desalination system, which was composed of a humidifier with packs and a bubble column dehumidifier, was proposed by Chehayeb [10]. The impacts from the mass flow rate ratio on the entropy generation rate as well as driving forces were analyzed. In light of a generalized effectiveness for the humidification and dehumidification process, air extraction/injection measures were also used to improve the system performance. Rajaseenivasan [11] proposed a bubble column humidification-dehumidification desalination system with the biomass as the driving power, which was made up of bubble column humidifier, dehumidifier, a biomass stove and an air heat exchanger. The relevant experiments were first achieved in the bubble column humidifier to determine the water depth, bubble pipe hole diameter as well as the water temperature. It is seen that the humidifier capacity was augmented with the elevation of the water depth, water temperature, air mass flow rate, cooling water flow rate, and reduction of the diameter for the bubble pipe hole. It is found that

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Nomenclature

Roman symbols

a	specific area ($m^2 m^{-3}$)
A	heat transfer surface area (m^2)
C	cost ($)
b	channel height of the plate heat exchangers (mm)
c_p	specific heat ($J kg^{-1} K^{-1}$)
d	diameter (m)
D_{WHRE}	distance along the waste heat recover exchangers (m)
h	enthalpy ($kJ kg^{-1}$), heat transfer coefficient ($W K^{-1} m^{-2}$)
H	total enthalpy (kW); packing height (m)
k	mass transfer coefficient ($kg m^{-2} s^{-1}$)
m	mass flow rate ($kg s^{-1}$)
p	pressure (MPa)
Q	heat load (kW)
Re	Reynolds number
S	concentration of seawater ($g kg^{-1}$)
S_p	plate area (mm^2)
T	temperature (K)
w	humidity ratio ($g kg^{-1}$)
W	channel width (mm)

Greek letters

β	plate chevron angle (°)
δ	plate thickness (mm)
φ	expansion coefficient
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 ($kJ kg^{-1}$)

Subscripts

a	air
b	brine
d	dehumidifier; dry
da	dry air
e	exhaust
f	fan
GOR	gained-output-ratio
h	humidifier
i	inlet
$LMTD$	log mean temperature difference
o	outlet
p	plate; pump
sw	seawater
t	total
$UAWP$	unit area of water production
$UCWP$	unit cost of water production
w	water; wall
$WHRE$	waste heat recover exchanger

the water temperature is critical to control the humidifier performance in comparison with other parameters. Furthermore, better specific humidity was observed with a bubble pipe hole diameter of 1 mm, water depth of 170 mm and water temperature of 333.15 K. Finally, a correlation was concluded to assess the mass transfer coefficient, which has a maximum deviation of 9% from the experimental results. Analysis based on the second law of thermodynamics was also advised to ensure the practicability of the HDH desalination systems [12,13]. Mistry [14] accompanied the analysis of entropy generation rate for a closed-air and open-water configurations with both air and water heaters in the HDH desalination system on the basis of the established entropy generation and exergetic equations. He [15] proposed a coupled system of the water-heated HDH desalination system and the plate heat exchangers, and the effect from the operation pressure on the

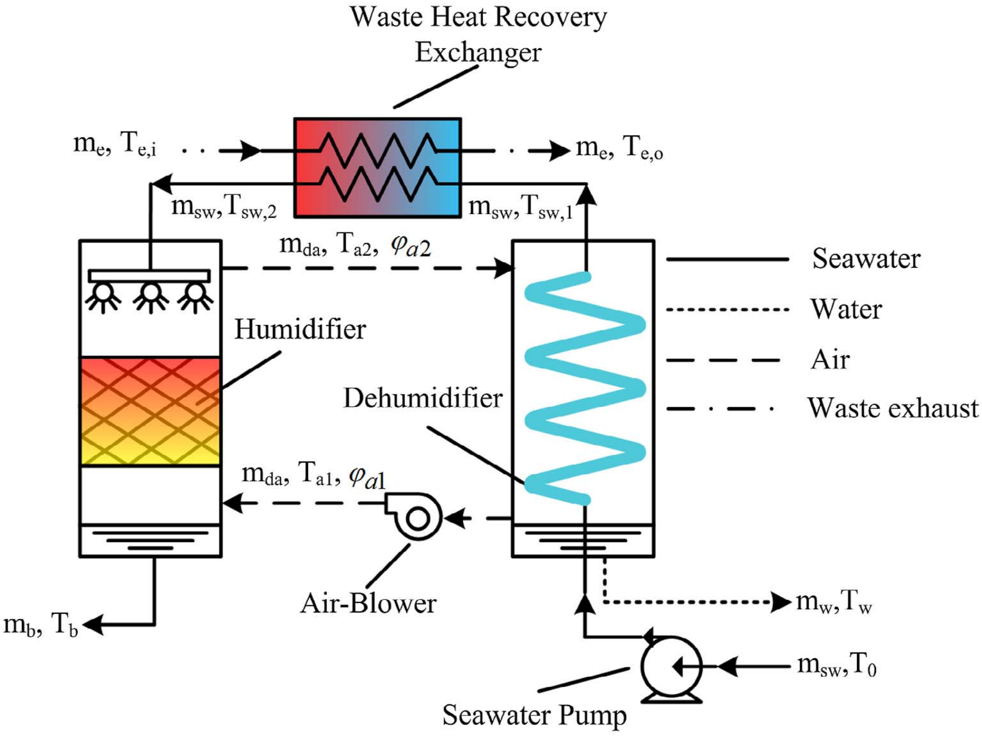

Fig. 1. Configurations of the water-heated HDH desalination system with waste heat recovery.