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Parametric analysis of an air-heated humidification-dehumidification (HDH) desalination system with waste heat recovery

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HIGHLIGHTS

- Air-heated HDH desalination with waste heat recovery is proposed.
- Performance of the desalination system is calculated.
- Second law of thermodynamics is applied to judge the feasibility of the desalination system.
- Sensitivity analysis at different parameters is calculated and presented.

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ABSTRACT

Industrial waste heat is effective to provide power for the desalination system to acquire distilled water. In this paper, exhaust gas is drawn into the plate heat exchangers (PHEs) to heat the circulated humid air within the humidification dehumidification (HDH) desalination unit. Based on the governing equations of the components and the fixed-effectiveness model, key parameters are prescribed to accomplish the performance analysis of the HDH desalination system, and the relevant recovery results of the waste heat are also attained. The simulation results present that the balance condition of the dehumidifier is inaccessible due to a negative specific entropy generation of the dehumidifier in spite of the obtained best performance at such point. It is summarized that high values of the component effectiveness and the initial temperature as well as the vacuum environment are beneficial to raise the performance of the desalination system and reduce the heat transfer surface area for the PHEs. Moreover, the elevation of the top temperature contributes to a slight elevation of the gained-output-ratio (GOR), while the relevant heat transfer surface area of the PHEs increases.

1. Introduction

In virtue of the serious freshwater supply all over the world, different types of desalination systems were proposed to separate distillated water from the seawater. For example, large scale of desalination plants based on the method of multi-effect evaporator (MEE), multi-stage flash (MSF), thermal vapor compression (TVR), mechanical vapor compression (MVC) and reverse osmosis (RO) were put into applications [1–3]. However, huge amount of energy consumption, fuel or mechanical energy, must be input into the desalination stations. Hence, such large scale desalination systems are not suitable for the places which are short of fossil fuel or electricity, and the corresponding small scale applications will have a very limited energy utilization efficiency.

In order to satisfy the small scale demand of freshwater supply, the relevant desalination pattern with a higher efficiency should be provided. As one of the most promising desalination pattern for small-scale water requirement, the HDH desalination systems have been proposed and developed rapidly in the recent years [4–6].

The HDH desalination system can be divided into three basic types, the water-heated, air-heated and dual heated type [7,8]. For the water-heated type, seawater is heated to power the HDH desalination system. Mcgovern [9] proposed a water-heated HDH desalination system with and without single extraction [7], and the corresponding performance was calculated and analyzed. The results showed that for the cycles with an initial temperature of 298 K and a top air temperature of 343 K, the peak value of GOR arrived at approximately GOR = 3.5 for the general system and about GOR = 14 for the improved single extraction one. For the aspect of the recovery ratio, it was limited to approximately 7% without extractions and 11% with a single extraction. As a result, it was demonstrated that the method of extraction was efficient to raise the performance of the HDH desalination system.

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Nomenclature

Roman symbols

A	heat transfer surface area (m^2)
b	channel height of the plate LGHC (m)
cp	specific heat ($Jkg^{-1} K^{-1}$)
Dh	hydraulic diameter (m)
h	convective heat transfer coefficient ($Wm^2 K^{-1}$); enthalpy ($kJ\ kg^{-1}$)
m	mass flow rate (kgs^{-1})
M	Molecular weight ($g\ mol^{-1}$)
Nu	Nusselt number
p	pressure (MPa); wet perimeter (m)
Q	heat load (kW)
Pr	Prandtl number
Re	Reynolds number
s	specific entropy generation
S	concentration of seawater ($g\ kg^{-1}$)
Δtm	log mean temperature difference (K)
T	temperature (K)
U	overall coefficient ($Wm^{-2} K^{-1}$)
v	velocity (ms^{-1})
w	humidity ratio ($g\ kg^{-1}$)
W	channel width (m)

Greek letters

β	plate chevron angle (°)
δ	plate thickness (m)
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 ($Wm^{-1}\ K^{-1}$)
γ	latent heat ($kJ\ kg^{-1}$)

Subscripts

a	air
b	brine
ch	channel
d	dehumidifier
da	dry air
e	exhaust
gen	generation
h	humidifier
i	inlet
o	outlet
p	plate
r	recovery
sw	seawater
t	total
dw	distillated water

Hamed [10] also proposed a water-heated solar desalination unit, and theoretical simulation model with energy equations of each component was established to evaluate the relevant performance and the productivity. Two periods: the first one from 9 am to 17 pm, the second after preheating before entering the humidifier at 13 pm to 17 pm, were appointed to calculate the freshwater production of the proposed system. The final results indicated that the highest distilled water production is found in the second period. Moreover, the relevant experimental system was built to investigate the heat and mass transfer process within the system, and a comparison between experimental and theoretical results presented a good agreement and gave the evidence that the proposed theoretical model is valid to be applied for the solar HDH desalination system under different boundary conditions.

For the air-heated type, all the driven power was obtained through the humid air and the heat sources. A parabolic trough solar collector (PTSC) was advised to be integrated into an open air, open water, air-heated HDH system by Al-Sulaiman [11], 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 were well suited for air heated HDH systems in 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. Farsad [12] suggested the governing equations for a solar HDH desalination system. The amount of fresh water production was analyzed with the advised equations, and the sensitivity analysis was achieved with the design of experiment method. Finally, the optimum conditions of the desalination plant were obtained.

For the dual heated type, humid air and seawater were both heated for a better efficiency and higher freshwater production. Yildirm [13] analyzed the performance of a water and air heated solar powered HDH desalination system for various operating and design parameters under climatological conditions of Antalya, Turkey. The related mathematical model was proposed and the corresponding governing conservation equations were numerically solved with the Fourth order Runge-Kutta method. Daily and annual yields were calculated for different working conditions of the desalination system.

Elminshawy [14] investigated the impacts from the induced atmospheric air and water heaters, external reflector and weather conditions on the performance of HDH system. Experiments were accomplished under the climatological conditions of Madinah, Saudi Arabia in April 2014. Performance of the HDH system was obtained with and without the water heaters and reflector. Experimental results presented that the daily freshwater production of the HDH system has improved when the water heaters and reflector were applied. A significant increase of the water production was obtained for still configured with two water heaters at 500 W each and a reflector tilted at 20° compared to that without heaters and reflector.

From the literature survey, It was concluded that the research of the humidification dehumidification technology focus on the utilization of the solar energy. Obviously, the combination of solar energy and the HDH desalination is an excellent configuration to produce freshwater. However, the intermittence of the solar radiation is the inherent disadvantages for such solar-driven desalination systems without energy storage unit, and the stable water supply is the rigid demand for the desalination system in the most cases. As a result, the abundant waste heat can be recovered to satisfy the stable requirement of the freshwater, while the coupled systems between the air-heated humidification dehumidification desalination unit, which has a higher value of GOR than the water-heated type verified by Narayan [7], and the waste heat were not involved [15,16]. Furthermore, the performance of the water-heated HDH desalination system powered by waste heat was simulated [17], and the detailed relationship between the critical parameters and the performance of the air-heated HDH desalination system was not illustrated [18]. In the present paper, the air-heated HDH desalination system with the plate heat exchangers to recover the waste heat is structured. The corresponding mathematical equations based on the first and second law of thermodynamics are proposed and validated [19,20]. Performance of the air-heated HDH desalination system at different designated conditions is calculated and illustrated. The investigation method as well as the simulated results provides significant references to structure and optimize the HDH desalination system.

2. Principle description of the air-heated HDH desalination system

As shown in Fig. 1, it is found that the air-heated desalination system mainly consists of three components, the direct contact humidifier,