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A study on the maximum gained output ratio of single-effect solar humidification-dehumidification desalination

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A B S T R A C T

Based on the minimum work requirement for the humidification- dehumidification (HDH) desalination processes, the potential maximum gained output ratio (GOR) of a single-effect closed-air open-water (CAOW) water-heated solar humidification-dehumidification desalination system is calculated in this paper. The theoretical results show that the minimum work requirement for an ideal HDH desalination system increases with the operating temperature. Moreover, when concentration ratio of used solar concentrators changes, maximum GOR has slightly change. Higher than 340 K, the maximum GOR will evidently increase with the operating temperature. When the concentration ratio of used solar concentrators increases, the maximum GOR rises. The calculation results also indicate that the maximum GOR for a solar HDH desalination system is generally fewer than 12.5 (370 K) according to different concentration ratios. Mass concentration of sodium chloride has slightly effect on maximum GOR. The effect on evaporation work is too small to compare with dehumidification work. Having set the top limit of HDH desalination system performance will ensure to see the potential of increase of these system's performance.

1. Introduction

Humidification-dehumidification (HDH) desalination method is considered to be an important developing direction in seawater desalination field, especially for small scale systems in remote areas. HDH desalination technology has many advantages over other methods, such as running particularly stable, simple control system, no need to strict pretreatment, no scaling problems, operating at atmospheric pressure, having low maintenance demand, etc. (Parekh et al., 2004; Bourouni et al., 2001). It is also very easy to be combined with solar applications. When comparing the HDH desalination systems to solar stills, the HDH desalination systems have significantly higher GOR than solar stills. GOR is the ratio of produced fresh water multiplied with evaporation enthalpy to the energy input of the system. This ratio is important to determine the area of solar collector for freshwater demand. Many researches have contributed their efforts to improve the performance of the HDH system (Fath and Ghazy, 2002; Goosen et al., 2000, 2003; Narayan et al., 2010).

This system use humidification and dehumidification to produce freshwater from seawater, since they have been existing in nature early. For example, sunlight shines on the sea to produce the vapor; the vapor rises with air to the sky and forms cloud; finally, the cloud shapes rain and falls down to the ground to obtain the freshwater. However, it is only several decades for humankind using this process to produce freshwater efficiently. In order to increase the efficiencies, lots of studies have been conducted by researches. In these studies various system configurations and mathematical models have been proposed. Müller-Holst et al. (1998) designed a small multi effect HDH system and obtained 4.5 of GOR which testified the effectiveness of this kind of system. Eettouney and Rizzuti (2006) also analyzed and optimized the performance of a solar HDH desalination system from the thermodynamic aspect. For further acquiring the higher efficiency of the system, Hou et al. (2005) did the performance optimization using pinch technology which is a theoretical solution to improve system efficiency. Narayan et al. (2010) analyzed the thermodynamic performance of various HDH systems and proposed novel higher performance variations. Lastly, Kang et al. (2016) also did pinch analysis for optimizing multi effect solar HDH system.

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Nomenclature

C_p	specific heat [kJ/kg K]
C	concentration ratio of solar heat collection system
f	angle coefficient of solar concentrator
h	specific enthalpy [kJ/kg]
h_{fg}	condensation latent heat of pure water
I	solar irradiance on the collector surface
m	mass flow rate [kg/s]
P	total pressure of the air-water vapor mixture [kPa]
P_a	partial pressure of air in the air-water vapor mixture [kPa]
P_g	saturation pressure of water vapor [kPa]
P_v	partial pressure of water vapor in the air-water vapor mixture [kPa]
Q, q	heat flow [kW]
s	specific entropy [kJ/kg K]
T	temperature [K]
w	specific work required for air conditioning process [kJ/kg]
W	work required for air condition process [kW]
σ	Stephen Boltzmann constant
ω	humidity ratio [kg_w/kg_a]
Φ	relative humidity
Ψ	specific exergy [kJ/kg]
GOR	gained output ratio
HDH	humidification and dehumidification

Subscripts

a	air
amb	ambient
abs	absorber surface
col	saline water inlet to the solar collector system
B	brine outlet from the humidifier
d	dead state
e	evaporation process
f	saturated liquid water
g	saturated water vapor
i	state index
in	supply into the system
int	internal ideal condition
l	liquid water
numbers	state indices
rev	reversible
s	surface
sat	saturation
t	total
u	useful
v	water vapor
0	ambient
HD	air outlet from the humidifier
DH	air outlet from the dehumidifier

Recently, although the technology and efficiency of solar HDH system have been developed greatly, however, the question can be asked that what its theoretical maximum gained output ratio (GOR) for an ideal solar HDH desalination system is. In order to answer this question, solar HDH desalination process should be separated into four steps: seawater evaporating, vapor mixing with air (corresponding the humidification process), vapor condensing in the air (corresponding the dehumidification process) and solar supplying heat. If each step is done perfectly, then maximum GOR is obtained.

From the perspective of thermodynamics, the humidification process is actually the mixing process of air and water vapor, while the dehumidification process is the separation process of air and water vapor. The humidification produces exergy loss, while the dehumidification demands minimum work required. As discussed above, three steps are needed to complete the whole process of HDH desalination. Firstly, evaporated water vapor from seawater, which needs energy that can be recovered partly from the condensation process. Then, evaporated water is mixed with air, which costs no energy but leads to work loss. Finally, separating water vapor from air, named as dehumidification process, requires energy and demands minimum work required. Therefore, the sum of works of the two steps to complete a HDH desalination cycle is needed. If each step requires the minimum work, the required work of desalination process reaches its minimum value. There are, actually, a lot of scholars who have studied the minimum work required of the desalination. For example, Cerci (2002) and Cerci et al. (1999) deduced the minimum work required equation of seawater evaporation process when the seawater or saline water is at different concentrations. He proved that the minimum power consumption rises when the feed salinity increases. Qian et al., 2013 worked out the theoretical equation for the minimum work required of desalination process based on the chemical potential change of seawater composition. Kalogirou (2005) analyzed desalting process and constructed exergy steady balance equation by adopting the classical theory of thermodynamics.

On the other hand, many scholars have studied the minimum work required for dehumidification process. Alhazmy (2007) explained the equations about the minimum work requirement for dehumidification process. Camacho (1999) and Cengle et al. (1999) and Cengle and Boles (2002) studied the work required of isothermal process for condensing water from the atmosphere and gave a theoretical value in different temperature. All of these studies establish a foundation to further explore minimum work required of the solar-powered desalination based on air HDH.

However, an idealized analysis of a complete solar-powered HDH desalination system has not been put into practiced yet. It is thought that conducting research on this issue is beneficial for actual system designers to improve their design ideas. From Müller-Holst et al. (1998) it can be found that among all HDH systems, the multi-effect closed-air open-water (CAOW) water-heated system is the most energy efficient. This paper only does research on the single-effect CAOW water-heated system with very good representative (Narayan et al., 2010). The minimum work required of an idealized solar-powered HDH desalination system can also be as an evaluation indicator to evaluate the actual engineering, which makes this research meaningful.

2. Humidification-dehumidification (HDH) desalination

Fig. 1 shows the basic operation process of an ideal single-effect HDH desalination system. In this system, cold seawater first enters the dehumidifier, cooling humid air circulated from the fans and precipitating freshwater. At the same time, the seawater is heated, then seawater enters the heater to be further heated and then returns to humidifier to evaporate. Finally, the sea water turns into concentrated brine and it is discharged out of the humidifier.