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Thermodynamic balancing of the humidification dehumidification desalination system by mass extraction and injection

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ABSTRACT

Humidification dehumidification (HDH) is a promising technology for small scale seawater desalination and has received widespread attention in recent years. The biggest roadblock to commercialization of this technology is its relatively high energy consumption. In this paper, we propose thermodynamic balancing of the humidifier or the dehumidifier through mass extraction and injection as a potential means of reducing the energy consumption of these systems. Balancing minimizes the entropy generation caused by imbalance in driving temperature and concentration differences. We outline a procedure to model the system, using on-design component variables, such that continuous or discrete extraction and/or injection of air from the humidifier to the dehumidifier or *vice versa* can be analyzed. We present an extraction profile (mass flow rate ratio versus non-dimensional position) in the dehumidifier and the humidifier for attaining close to complete thermodynamic reversibility in an HDH system with a 100% effective humidifier and dehumidifier. Further, we have examined in detail the effect of having finite-sized systems, of balancing the humidifier versus the dehumidifier, and that of the number of extractions.

1. Introduction

When finite time thermodynamics is used to optimize the energy efficiency of thermal systems, the optimal design is one which produces the minimum entropy within the constraints of the problem (such as fixed size or cost). In this study, we apply this well-established principle to the thermal design of combined heat and mass exchange devices (dehumidifiers and humidifiers) for improving the energy efficiency of humidification dehumidification (HDH) desalination systems.

HDH is a distillation technology which operates using air as a carrier gas [1–3] to shuttle vapor and energy between the evaporation and condensation processes. The simplest version of this technology has a humidifier, a dehumidifier, and a heater to heat the seawater stream. Studies have been conducted on the effect of entropy generation on the thermal design of the HDH system [4,5] and it has been found that reducing the total entropy generated (per unit amount of water distilled) improves the energy efficiency (measured in terms of the gained-output-ratio or GOR). It has also been reported that incorporating mass extractions and injections to vary the water-to-air mass flow rate ratio in the combined heat and mass transfer devices (like the humidifier and the dehumidifier) can potentially help in reducing entropy production in those devices [6]. In the present study, we report a comprehensive thermodynamic analysis to understand how to design for the aforementioned mass extractions and injections in the HDH system. This design (discussed in the succeeding sections) draws upon the fundamental observation that there is a single value of water-to-air mass flow rate ratio (for any given boundary conditions and component effectivenesses) at which the system performs optimally [3].

A schematic diagram of an embodiment of the HDH system with mass extractions and injections is shown in Fig. 1. The system shown here is a water-heated, closed-air, open-water system with three air extractions from the humidifier into the dehumidifier. States a to d are used to represent various states of the seawater stream and states e and f represent that of moist air before and after dehumidification. There are several other embodiments of the system possible based on the various classifications of HDH listed by Narayan et al. [1].

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Nomenclature

Acronyms

GOR	gained output ratio
HDH	humidification dehumidification
HE	heat exchanger
HME	heat and mass exchanger
TTD	terminal temperature difference

Symbols

c_p	specific heat capacity at constant pressure (J/kg · K)
$\dot{H}$	total enthalpy rate (W)
g	specific gibbs energy (J/kg)
h	specific enthalpy (J/kg)
h^*	specific enthalpy (J/kg dry air)
h_{fg}	specific enthalpy of vaporization (J/kg)
HCR	control volume based modified heat capacity rate ratio for HME devices (–)
m_r	water-to-air mass flow rate ratio (–)
$\dot{m}$	mass flow rate (kg/s)
N	number of extraction (–)
P	absolute pressure (Pa)
$\dot{Q}$	heat transfer rate (W)
RR	recovery ratio (%)
s	specific entropy (J/kg · K)
sal	feed water salinity (g/kg)
$\dot{S}_{gen}$	entropy generation rate (W/K)
T	temperature (°C)

Greek

Δ	difference or change
ε	energy based effectiveness (–)
Ψ	enthalpy pinch (kJ/kg dry air)
Ψ_{TD}	terminal enthalpy pinch (kJ/kg dry air)
η_{tvc}	reversible entrainment efficiency for a TVC (–)
η_e	isentropic efficiency for an expander (–)
ϕ	relative humidity (–)
ω	absolute humidity (kg water vapor per kg dry air)

Subscripts

a	humid air
c	cold stream
deh	dehumidifier
da	dry air
h	hot stream
hum	humidifier
HE	heat exchanger
in	entering
int	water–vapor interface
max	maximum
$local$	defined locally
out	leaving
pw	pure water
rev	reversible
w	seawater

Thermodynamic states

a	seawater entering the dehumidifier
b	preheated seawater leaving the dehumidifier
c	seawater entering the humidifier from the brine heater
d	brine reject leaving the humidifier
e	moist air entering the dehumidifier
ex	moist air state at which mass extraction and injection is carried out in single extraction cases
f	Relatively dry air entering the humidifier
g	air at an arbitrary intermediate location in the dehumidifier
i	seawater at an arbitrary intermediate location in the dehumidifier

1.1. Literature review

Even though there has been no clear conceptual understanding of how the thermal design of HDH systems with mass extraction/injection should be carried out, a small number of studies in literature discuss limited performance characteristics of these systems. Müller–Holst pioneered the thermal balancing of HDH systems by proposing to balance the stream-to-stream temperature difference in the HME devices by 'continuous' variation of the water-to-air mass flow rate ratio [7,8]. The moist air in the proposed system was circulated using natural convection and the mass flow rate of this stream was varied by strategically placed extraction and injection ports in the humidifier and the dehumidifiers respectively. An optimized thermal energy consumption of 120 kWh/m^3 (≈450 kJ/kg) was reported for this system.

Zamen et al. [9] reported a novel 'multi-stage process' which was designed for varying the water-to-air mass flow rate ratio. This was achieved by having multiple stages of humidification and dehumidification in series with separate air flow for each stage and a common brine flow. A similar design was also reported by Schlickum [10] and Hou [11]. Zamen et al. [9] used a temperature pinch (defined as the minimum stream-to-stream temperature difference in the HME device) between the water and the air streams to define the performance of the system. For a four stage system with component pinch of 4 °C, at a feed water temperature of 20 °C and a top brine temperature of 70 °C, Zamen et al. reported an energy consumption of slightly less than 800 kJ/kg.

Brendel [12,13] invented a novel forced convection driven HDH system in which water was extracted from several locations in between the humidifier and sent to corresponding locations in the dehumidifier. This was done such that the temperature profiles were balanced (as was the case with Zamen et al. [9]). In a recent publication, Thiel and Lienhard [14] have shown that in order to attain the thermodynamic optimum in HME devices we have to consider both temperature, and concentration profiles and that the optimum lies closer to a balanced humidity profile than a balanced temperature profile. This finding is discussed further in Section 2.

Younis et al. [15] studied air extraction and injection in forced convection driven HDH systems. They found that having two extractions of air from the humidifier to the dehumidifier decreased the energy consumption of the system to 800 kJ/kg. Like in several other publications [7,12,9,16], they used enthalpy-temperature diagrams to demonstrate the effect of extraction on HDH system design. McGovern et al. [16] pinoored the use of the graphical technique and highlighted the important approximations that need to be made to use it for HDH system design.

Bourouni et al. [2] in a review of the HDH technology reported that a few other authors [17] studied air extractions in HDH systems and reported performance enhancements as a result of such