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Thermodynamic balancing of a fixed-size two-stage humidification dehumidification desalination system

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HIGHLIGHTS

- A robust heat and mass transfer model of a two-stage HDH system is implemented.
- A generalized energy effectiveness is proposed for heat and mass exchangers.
- Criteria for optimal energy efficiency and water production are given.
- A thorough analysis is given on the proper direction of extraction.

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ABSTRACT

Humidification dehumidification (HDH) is a desalination technology that has shown promise in small scale, decentralized applications. Previous studies on the multi-staging of HDH have used fixed-effectiveness models which do not explicitly account for transport processes in the components. However, to fully understand the effect of the variation of the mass flow rate ratio, it is necessary to implement heat and mass transfer models of the HDH system. In this paper, we model an HDH system consisting of a packed-bed humidifier and a multi-tray bubble column dehumidifier. We study the effect of the mass flow rate ratio on the performance of a fixed-size system, and we consider its effect on the entropy generation and the driving forces for heat and mass transfer. In addition, we define a generalized energy effectiveness for heat and mass exchangers. We also implement an air extraction/injection and simulate a wide range of operating conditions. We define criteria for the best system performance, and we study the effect of the distribution of available area between separate stages. We also present a thorough explanation of why the direction of extraction should always be from the humidifier to the dehumidifier.

1. Introduction

Humidification dehumidification (HDH) is a desalination technology that has received wide attention in recent years. Although it does not compete with existing technologies for desalinating seawater in medium and large scale applications, HDH can be advantageous in decentralized, off-grid desalination applications where fresh water demand ranges up to several thousand cubic meters per day [1,2]. In addition, the technology does not use membranes and does not include hot metal surfaces, which allows it to treat highly saline water with some oil content without requiring expensive corrosion resistant metals. HDH has recently been commercialized and has succeeded in treating produced water from hydraulically fractured oil and gas wells [3].

A typical HDH system consists of a humidifier, a dehumidifier, and a heater. In this paper we model a water-heated, closed-air, open-water HDH cycle. As shown in Fig. 1, cold air enters the humidifier where it is exposed to hot saline water, which increases its temperature and water content. The hot moist air then enters the dehumidifier where it loses heat to a feed stream of cold saline water flowing through a coil. Water vapor condenses in the dehumidifier and exits the system as a stream of fresh liquid water. The more we preheat the saline water in the dehumidifier the less heat we have to supply in the heater. Improving the energy efficiency of an HDH system is therefore a question of reusing the heat of condensation to heat the feed stream to the highest possible temperature before sending it to the heater.

1.1. Bubble column dehumidifiers in HDH

A major issue that made early HDH systems difficult to commercialize was their need for very large dehumidifiers [4,5] (up to 30 m^2 for a

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Nomenclature

Acronyms

GOR	gained output ratio
HCR	control volume based modified heat capacity rate ratio for HME devices
HDH	humidification dehumidification
HE	heat exchanger
MR	water-to-air mass flow rate ratio
RR	recovery ratio

Symbols

a	surface area per unit volume of packing [m^2/m^3]
c_p	specific heat capacity at constant pressure [J/kg·K]
D	diameter [m]
g	gravitational acceleration [m/s^2]
$\dot{H}$	total enthalpy rate [W]
H	humidifier height [m]
h	specific enthalpy [J/kg]
h^*	specific enthalpy [J/kg dry air]
h_{fg}	specific enthalpy of vaporization [J/kg]
h_t	heat transfer coefficient [W/m^2-K]
K	mass transfer coefficient [kg/m^2-s]
k	thermal conductivity [W/m-K]
Le_f	Lewis factor [–]
$\dot{m}$	mass flow rate [kg/s]
Me	Merkel number, also KaV/L [–]
N_t	number of trays in the dehumidifier [–]
Nu_D	Nusselt number based on the diameter [–]
P	absolute pressure [Pa]
Pr	Prandtl number [–]
R	thermal resistance [K/W]
Re	Reynolds number [–]
$\dot{Q}$	heat transfer rate [W]
$\dot{Q}_{in}$	heat input to the heater [W]
S	Salinity [ppt]
T	temperature [°C]
V	packing volume [m^3]
V_g	gas superficial velocity [m/s]

Greek

Δ	difference or change
ε	energy based effectiveness [–]
μ	dynamic viscosity [Pa s]
Ψ	enthalpy pinch [kJ/kg dry air]
ρ	density [kg/m^3]
ω	absolute humidity [kg water vapor per kg dry air]

Subscripts

1	colder stage
2	hotter stage
a	moist air
c	cold stream
col	column
cond	condensate
d	dehumidifier
da	dry air
deh	dehumidifier
f	liquid water
h	humidifier or hot stream
hum	humidifier
HE	heat exchanger
in	entering or inner
lm	logarithmic mean
loc	local quantity
max	maximum
out	leaving
pw	pure water
sa	saturation at air temperature
ss	supersaturation
sw	saturation at water temperature
v	water vapor
w	saline water

1 m^3/day system [6]), which increased their cost of water production greatly. Dehumidifiers contain a very large concentration of air, a non-condensable gas, which leads to very low mass transfer coefficients and increases the surface area needed in conventional dehumidifiers. As a solution to this issue, Narayan et al. [7] suggested the use of short bubble column dehumidifiers in HDH. They measured heat transfer rates that were an order of magnitude higher than those operating in the film condensation regime.

A bubble column is a heat and mass exchanger which, in the case of HDH, serves to transfer heat from a hot moist air stream to a saline feed water stream. Saline water is circulated through a curved coil that is submerged in a column of fresh water, and hot moist air is bubbled from the bottom of the column through a sparger. The air is cooled and dehumidified by transferring heat and mass to the column of fresh water, which in turn transfers the heat to the saline water inside the coil.

Recent studies by Tow and Lienhard [8–10] resulted in an accurate model of bubble columns that was experimentally validated. The model is used in this study, and is discussed in greater detail in Section 2.1. Tow and Lienhard [11,12] also measured heat transfer rates up to more than 8000 W/m^2-K in shallow bubble columns, further justifying their use in the dehumidification side of an HDH system.

Although the air and saline water circulate in opposite directions, the bubble column is still effectively a parallel flow configuration: both streams exchange heat with the same pool of fresh water which is at a constant temperature. This means that the streams can at best exit at the same temperature, which is that of the column of fresh water. As shown in Fig. 2(a), the water will exit the bubble column at a temperature that is much colder than that of the air inlet. The solution to this issue is to stack up multiple columns, each at a different

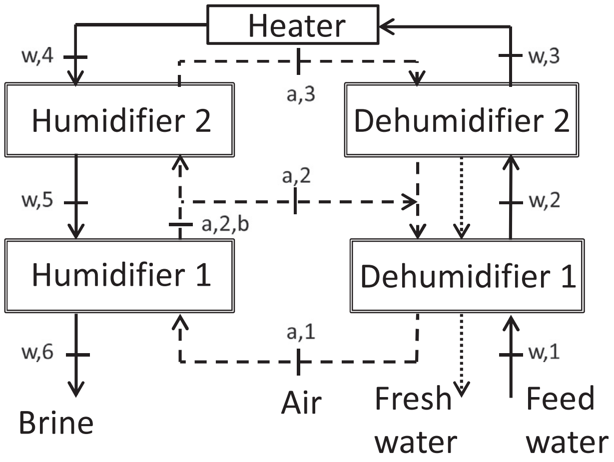

Fig. 1. Schematic diagram representing a water-heated, closed-air, open-water HDH system with a single extraction.