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Performance analysis of a heat pump driven humidification-dehumidification desalination system

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ABSTRACT

In this paper, a humidification-dehumidification desalination HDH cycle with direct contact dehumidifier is coupled with a heat pump. The heat pump is introduced in order to simultaneously supply the cooling and heating loads of the HDH cycle. Next, by implementing a mathematical model, the performance of the system is investigated under different working conditions. To incorporate the humidifier and dehumidifier effectiveness into the theoretical modeling, the ε-NTU correlation of the heat and mass transfer device is utilized. Performance parameters such as specific electrical energy consumption (SEEC), recovery ratio (RR) and coefficient of performance (COP) are employed for evaluating the system performance. The fully coupled condition of the HDH system with no extra cooling or heating scenarios is investigated. It is shown that a given saline water and freshwater temperatures, a fully coupled HDH system with the heat pump without adding the extra cooler can be achieved by alternating mass flow rate ratio of either seawater to freshwater or seawater to dry air.

1. Introduction

Fresh water is one of the vital needs for societies all around the world. Desalination is the process of producing fresh water from saline or impure water. Various types of desalination methods have been proposed and developed by researchers and can be categorized into membrane-based or thermal based methods.

The most widely commercialized desalination processes based on evaporation technique are multi-stage flash distillation, multiple effect distillation and vapor compression. The second category of desalination processes uses membrane technologies including reverse osmosis, electrodialysis and membrane distillation [1]. Humidification-dehumidification (HDH) desalination has recently attracted researcher's attention [2–5].

The main advantage of the HDH cycle is its small scale application which makes is a competitive alternative among other desalination technology for remote area water supply. The cycle can be operated reliably when it is assisted with a heat pump. Moreover, the components of the HDH system are usually affordably available on the market and the maintenance of the system in not complicated in terms of labor and tools [6,7].

There have been numerous works on non-direct condensers for dehumidification process in the HDH cycle [8–13]. Moreover, in this area, several studies have been performed to replace the thermal energy sources of the process from fossil fuels with renewable ones, especially solar energy [14–16]. In other studies, an alternative low-grade heat source such as industrial waste heat or geothermal [3,17–19] were considered for supplying the thermal energy demand of the cycle. To make the dehumidification process in non-direct HDH cycle cost-effective, an efficient low-cost method can be proposed to condense water vapor out of the air stream. With a large fraction of the air/vapor mixture being non-condensable, direct contact condensation is considerably more effective than film condensation.

There have been several studies done in this regard. Bharathan et al. [20] initially introduced a direct contact condenser approach to enhance the heat transfer rate in presence of non-condensable gas. Klausner et al. [21] fabricated a laboratory scale direct contact condenser to study the variation of temperature, humidity and condensation rate through the condenser system. They evaluated their result by considering a finite volume method for analyzing the direct contact packing condenser. Yi Li et al. [22] studied the performance characteristics of HDH desalination with a DC dehumidifier desalination process utilizing heat and mass transfer analysis. They also studied the performance of a DC dehumidifier using a laboratory scale setup [23] under different conditions. Alnaimat et al. [24–26] performed transient analysis of the HDH with DC dehumidifier using a one-dimensional numerical solution [24] as well as a transient dynamic response with the same method [26]. They further examined the operation of their

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Nomenclature

Symbol

T	temperature (°C)
$\dot{m}$	flow rate (kg/s)
$\dot{Q}$	heat rate (kW)
$\dot{H}$	enthalpy rate (kW)
mr	Water to air mass flow rate ratio (–)
h	specific enthalpy (kJ/kg)
RR	recovery ratio (–)
c_p	specific heat capacity at constant pressure (kJ/kg·K)
$SEEC$	specific electrical energy consumption
COP	coefficient of performance
f	average slope of the saturated air enthalpy versus temperature (kJ/kg·K)
NTU	number of transferred units
Me	Merkel number
a	specific area (m^2/m^3)
H	packing height (m)
CR	heat capacity rate ratio
PR	pressure ratio (–)
$\dot{W}$	work (kW)

Greek letters

ω	absolute humidity of dry air or humidity ratio (kg_w/kg_a)
φ	relative humidity (–)
ε	effectiveness (–)
Δ	difference or change
η	efficiency (–)

Subscripts

a	air
da	dry air
dw	distilled water
b	bottom
t	top
sw	Seawater, saline water
fw	fresh water
max	maximum
m	middle
br	brine
h	humidifier
d	dehumidifier
in	input
out	output
1, 2, 3, 4	flow states
com	compressor
con	condenser
eva	evaporator
ref	refrigerant

Acronyms

CAOW	closed-air open-water system
CWOA	cold-water open-air
HDH	humidification-dehumidification
HME	heat and mass exchanger
DC	direct contact

solar driven HDH setup under various design and operating conditions [25].

Eslamimanesh and Hatamipour [27,28] conducted a theoretical analysis for the open-air open-water HDH cycle to study the effect of working parameters on water production rate as well as performed an economic study of the system. Niroomand et al. [29] investigated freshwater production, efficiency and effects of various parameters including air flow rate, conditions of inlet cold and hot water and velocity and diameter of droplets on the performance of the open-air HDH cycle with DC dehumidifier system. Mehrgoo and Amidpour investigated the optimum water production rate utilizing constructal design theory for a fixed-size HDH system [30]. Ettouney [31] introduced different types of dehumidifier including vapor compression, desiccant air drying and membrane air drying.

He et al. [32] studied a direct-contact HDH desalination system through a thermodynamic based mathematical model. They applied plate heat exchangers to recover waste heat for thermal energy consumption/requirements of the system. In another study, He et al. [33] used a mechanical compression heat pump to study the performance of the water-heated HDH with a non-direct dehumidifier. They reported maximum GOR of 5 and water production of 85 kg/h. Lawal [34,35] compared the performance of the heat pump assisted air-heated and water-heated HDH with non-direct dehumidifier desalination. By applying a mathematical model they investigated the influence of operating parameters on the performance of the system. They reported maximum recovery ratio and GOR of 4% and 10 for the system, respectively. Queiroz et al. [36] coupled a vapor compression heat pump directly to an adiabatic humidifier for purified water production by recirculation air. Xu et al. [37] experimentally studied a heat pump assisted water-heated HDH with non-direct dehumidifier system. They added an evaporator after the dehumidifier for extra cooling of the air and a solar collector after the condenser for additional heating of feed seawater. They reported maximum productivity of 12.38 kg/kW h. Shafii et al. [38] experimentally studied the performance of an open air-heated HDH system with a heat pump to heat air in the condenser and cool it down after humidification at the evaporator. They obtained highest yield and GOR of 2.79 kg/h and 2.08, respectively.

A lack of knowledge for the HDH with direct contact and heat pump to provide the energy requirements can be clearly observed from the literature. Therefore, in this study a comprehensive theoretical analysis of a heat pump driven HDH cycle with a DC dehumidifier was performed in order to investigate the effect of operational parameters on the specific energy consumption and water production of the system.

2. System description

Fig. 1 shows the overview of the heat pump assisted HDH with DC dehumidifier. It utilizes two heat and mass exchanger devices for producing distilled water. These are the humidifier and dehumidifier. There is simultaneous heat and mass transfer in heat and mass exchange (HME) devices due to temperature and concentration gradients between water and air. These HME devices consist of packing fill that provides high surface area for effective heat and mass transfer. To simultaneously provide the heating demand in the humidifier and cooling demand in the dehumidifier a heat pump is considered. It is used in order to cool down the fresh water after dehumidification process by transferring its gained heat to the working fluid of the heat pump. Also, the heat pump supplies the heating demand of the saline water at the same time in the high-temperature side by consuming electrical power in the compressor.

In the humidifier saline water is sprayed over packing fill after it is heated in the high temperature side of the heat pump. This is done to increase the vapor content of the air. Then, the hot moist air is transferred to the dehumidifier in which cold fresh water is sprayed over it.