Desalination xxx (xxxx) xxx–xxx

Contents lists available at ScienceDirect

Desalination

journal homepage: www.elsevier.com/locate/desal

Design strategies of conventional and modified closed-air open-water humidification dehumidification systems

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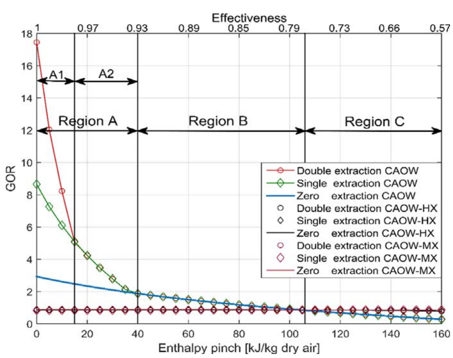
GRAPHICAL ABSTRACT



ARTICLE INFO

Keywords:
Desalination
Humidification-dehumidification
Extraction
Heat recovery
Enthalpy pinch

ABSTRACT

Humidification dehumidification (HDH) systems are robust and known to withstand a wide range of saline water without the need of complex maintenance. In this study, the closed-air open-water (CAOW) HDH arrangement is examined, which can easily be integrated with solar or other renewable resources. Also, this system is modified by incorporating heat recovery options for low performing units. The heat recovery process is executed through two approaches, (i) a mixing chamber and, (ii) by a heat exchanger. Thermal balancing through air extraction is evaluated for the basic as well as the modified cycles, particularly for high performing units. Zero, single and double extractions models are evaluated for the conventional CAOW water heated cycle. The performance of the systems is characterized into three operating regions (high, moderate and low) based on the effectiveness of the components. Based on the results of this evaluation, an operating scheme is then developed to decide where to use the conventional or the modified systems with or without extraction.

1. Introduction

There is about 40% of the world population that is suffering from the water shortage problems. It is expected to reach 60% by 2025 [1]. A large portion of the world population lives within 70 km of seashores [2], which qualifies for industrial desalination as a promising solution to this crisis. Industrial desalination is classified into thermal, mechanical and electrical techniques. One of the promising thermal techniques is the humidification-dehumidification (HDH) desalination system. The HDH desalination system is suitable for small-scale fresh-water production. Thus, it is more suitable for villages and small communities due to its simplicity. These systems are considered to have some advantages over other desalination technologies such as their capacity to operate over a wide range of untreated water quality with

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https://doi.org/10.1016/j.desal.2017.11.011
Received 8 July 2017; Received in revised form 9 October 2017; Accepted 6 November 2017
0011-9164/

Nomenclature

Acronyms

GOR	gained output ratio
HDH	humidification-dehumidification
HX	heat exchanger
MX	mixing chamber
CAOW	closed-air open-water

Symbols

$\dot{m}$	mass flow rate (kg/s)
M_r	water-to-air mass flow rate ratio (−)
$\dot{Q}$	heat transfer rate (kW)
h	specific enthalpy (kJ/kg)
h^*	specific enthalpy (kJ/kg dry air)
h_{fg}	specific enthalpy of vaporization (kJ/kg)
RR	recovery ratio (%)
m	slope of humidifier and dehumidifier line (C·kg dry air/kJ)
C	intersection of humidifier and dehumidifier line (°C)
c_p	specific heat capacity at constant pressure (kJ/kg·K)
tan	correspondent point at humidifier line to the tangent point at air curve
tan´	tangent point at air curve
X	salinity (ppm)
T	temperature (°C)

Greek

Δ	change
ε	effectiveness (−)
Ψ	enthalpy pinch (kJ/kg dry air)
ω	absolute humidity (kg water vapor per kg dry air)
φ	relative humidity (−)

Subscripts

0, 1, …	state points
a	air
b	brine
w	saline water
cw	cooling water
deh	dehumidifier
hum	humidifier
hx	heat exchanger
in	entering
pw	pure water
mix	mixer
ext	extraction point
b	brine

minimum maintenance requirements [3]. The basic drawbacks of HDH systems remain that the total heat input is relatively high compared to other conventional thermal desalination technologies; however, renewable energy as a source of heat input can be utilized in these systems.

Müller–Holst [4,5] proposed to vary the water-to-air mass flow rate ratio continuously in order to achieve thermal balancing of HDH systems. This variation will decrease stream-to-stream temperature difference. He made use of natural convection to circulate the moist air stream through ports in both the humidifier and dehumidifier. This circulation resulted in variation of the water-to-air mass flow rate ratio. After optimization, the system's specific energy consumption was 120 kWh/m^3 (≈ 450 kJ/kg). Another novel approach is to vary the water-to-air mass flow rate ratio was introduced by Zamen et al. [6]. They designed a multi-stage process, in which, HDH processes are executed in a sequence. The brine flow was common for all the stages, while the air flow was separate for each stage. Schlickum [7] and Hou [8] reported a similar design. Zamen et al. [6] have defined the system by the temperature pinch approach, which is commonly used in process industries. The total specific heat consumed by this system was about 800 kJ/kg. The humidifier and dehumidifier both had a temperature pinch of 4 °C, at a top- and bottom-cycle temperatures of 70 °C and 20 °C, respectively.

Another novel HDH system driven by forced convection was invented by Brendel [9,10]. Under the balanced temperature profiles, forced convection was used to extract water from the dehumidifier and was injected to the humidifier. This extraction process was executed at several points in both the humidifier and dehumidifier. Thiel and Lienhard [11] have stated that the optimization of heat and mass transfer exchanger (HME) devices, thermodynamically requires considering both the temperature and concentration profiles. They have shown that balancing humidity profile have more significance in the optimization of the system than balancing the temperature profile. Forced convection driven HDH systems with air extraction and injection have also been investigated by Younis et al. [12]. They have succeeded to increase the system efficiency as the specific energy consumption decreased to 800 kJ/kg. In their system, the air was extracted from two points in the humidifier and injected to the dehumidifier. They followed enthalpy-temperature diagrams, as used in several other publications [4,6,9,13], to illustrate the extraction impact on the design of HDH systems.

Thermal balancing by extracting air or water from the humidifier and injected it into the dehumidifier or vice versa has been investigated by Narayan et al. [14]. Mistry et al. [15] found that reducing the specific entropy would result in minimizing the GOR. Miller et al. [16] studied the effects of extraction on balancing enthalpy rates in HDH systems. They followed an effectiveness-based methodology. Their main conclusion was that extractions are better for systems that have a high effectiveness in both the humidifier and dehumidifier of an HDH system.

The variation of temperature pinch effect on both the recovery ratio (RR) and gain output ratio (GOR) has been studied by McGovern et al. [13]. They showed an increase in GOR from 3.5 to 14 by incorporating single water extraction by assuming that effective heat and mass transfer area to be very large. That increase was achieved by using bottom- and top-cycle temperatures of 25 °C and 70 °C, respectively. Furthermore, for a single water extraction and under same operating conditions, they reported an increase in RR from 7% to 11%.

Narayan et al. [17] defined a novel parameter called the enthalpy pinch approach. They used this parameter to balance HME devices since this parameter takes into account both heat and mass transfer processes that are occurring in HDH systems. Balanced systems that have zero extraction, one extraction and an infinite number of extractions were studied using the enthalpy pinch approach. An increase in the GOR from 2.6 to 4.0 for a system with single air extraction has been reported in an experimental study by Narayan et al. [18]. In their experimental study, the enthalpy pinch was 19 kJ/kg of dry air. The bottom- and top-cycle temperatures were 25 °C and 90 °C, respectively.

Chehayeb et al. [19] in continuation of the previous work by Narayan et al. [17] have investigated the effect of extractions on the GOR, RR, and the total heat input to the cycle. They examined a finite number of extractions and found that the smaller the enthalpy pinch,