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Performance evaluation of humidification-dehumidification (HDH) desalination systems with and without heat recovery options: An experimental and theoretical investigation

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ABSTRACT

Humidification dehumidification (HDH) desalination system is a thermal-based desalination technology that is suitable for small-scale water desalination applications. In this paper, we present an experimental and thermodynamic analysis of the energetic performance of two HDH cycles. The HDH cycles considered are the basic open-air open-water (OAOW) cycle and the modified closed-water open-air (CWOA) cycle with the options of brine recirculation. An experimental investigation is performed on the modified cycle to validate the theoretical model that is used to assess the energetic performance of both the basic and modified cycles. The theoretical model is found to be in a good agreement with the experimental data with a maximum percentage deviation of 5% from the experimental data. Furthermore, limiting cases of the system are explored. Within the limiting cases, the modified cycle recorded about 100% improvement in the energy performance over the basic cycle due to heat recovery process associated with the modified cycle. Additionally, a cost analysis was performed to determine the cost of freshwater production by the presented desalination cycles. Results show that the freshwater price varied from 4.10 to 6.55 $\$/m^3$ and 0.79 to 2.25 $\$/m^3$ for the basic OAOW HDH cycle and the modified CWOA HDH cycle, respectively.

1. Introduction

Over the last century, the demand for potable water has substantially increased due to the increase in human population, activities, and development such as agricultural, industrial and socio-economic development. In an attempt to address the problem of freshwater shortage, several desalination techniques have been developed to desalinate saline water. Humidification-dehumidification (HDH) desalination system is one of the most promising desalination technologies for a decentralized small-scale desalination process [1]. HDH desalination process has been used, investigated and improved over the years. These systems are suitable for small-scale freshwater production, and offer numerous advantages over other desalination technologies; however, the main drawback remains. That is, it requires a relatively high-energy compared to other desalination technologies [2]. HDH systems have an advantage over some other technologies, such as reverse osmosis, in that they involve a relatively simple, inexpensive components. It can operate over a wide range of raw water quality without the need for complex maintenance operations [2]. These systems are also reported to have a higher GOR over solar still. Other benefits of HDH systems include the ability to operate at low temperature, and the feasibility of being powered by sustainable energy resources such as solar and geothermal [3]. These systems may be classified according to whether air or water is heated and to the nature of air or water stream [4]. This work has been focused on open-air open-water (OAOW) and closed-water open-air (CWOA) HDH cycles.

Many studies on HDH system have been directed on optimizing and improving the performance of its components with the aim of improving the overall system performance. An innovative design that can reduce the dehumidifier size through direct contact HDH process has been studied by Niroomand et al. [5]. In the proposed system, air is dehumidified by spraying cold water to the hot and humid air stream, instead of using the conventional indirect condensers for the dehumidification process. Their results showed that the water production increases with decreasing initial velocity and diameter of water droplets. It was also found that the freshwater production and efficiency of the system increases with increasing hot water flow rate and temperature as well as by decreasing the cold water flow rate and temperature. Klausner et al. [6] used a direct-contact dehumidifier in combination with a shell-and-tube heat exchanger to provide enhanced condensation

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Nomenclature

Acronyms

CAOW	closed-air open-water
COE	the unit cost of electricity
CWOA	closed-water open-air
EPC	annual electric power cost
GOR	the gained output ratio
HCR	heat capacity rate ratio
HDH	humidification-dehumidification
MR	the water-to-air mass flow rate ratio
OAOW	open-air open-water
RR	recovery ratio (%)
SEC	specific energy consumption

Symbols

C_F	annual capital cost ($ yr^{-1})
C_P	unit product cost ($ m^{-3})
C_T	total annual cost ($ yr^{-1})
c_P	specific heat capacity at constant pressure (kJ kg^{-1} K^{-1})
f	plant availability
h	specific enthalpy (kJ kg^{-1})
h_{fg}	specific enthalpy of vaporization (kJ kg^{-1})
i	interest rate
L_C	annual labor cost ($ yr^{-1})
$\dot{m}$	mass flow rate (kg/s)
n	amortization years (life of the system)
P	Pressure (kPa)
$\dot{Q}$	heat transfer rate (kW)
T	temperature (°C)
X	salinity (ppm)
x	the fraction of saline water mass flow rate (kg/s)
y	the fraction of brine mass flow rate (kg/s)

Greek Symbols

ε	effectiveness
ω	absolute humidity (kg_w kg_a^{-1})
$\mathscr{L}$	the specific cost of operating a labor ($ m^{-3})

Subscripts

a	air
b	brine
cw	cooling water
deh	dehumidifier
fluid	working fluid
fw	freshwater
hum	humidifier
in	entering
intake	entering the stream
p	pump
0,1,...	state points

and improved heat recovery for the cycle. Dawoud et al. [7] theoretically investigated different possible cooling techniques for the condenser of a seawater greenhouse desalination system. The possible cooling techniques include; evaporative cooling for surface seawater, a cooling machine to cool the condenser coolant in a closed loop, or to utilize deep seawater as a condenser coolant. They suggested that evaporative cooling with surface seawater seems to be the most suitable cooling technology for the greenhouse condenser.

Ettouney [8] assessed different configurations of the HDH tower. The layouts included the conventional humidification system combined with each of the following units; lithium bromide absorption-desorption system, water condenser, vapor compressor, and water condenser, to condense the water vapor from the air. He showed the need to determine the most efficient design and operating conditions that result in a minimum product cost. In another study, Narayan et al. [9] assessed the thermodynamic performance of various HDH cycles through a theoretical cycle analysis. They also proposed different novel high-performance cycles including multi-extraction, multi-pressure systems. It is shown that the proposed high-performance cycle can attain a GOR > 5, which is expected to outperform many existing HDH systems. Sharqawy et al. [10] numerically investigated the design, performance, and optimization of two HDH cycles. They presented first-law based thermal analysis model, as well as performance charts, which can be used to determine the size of HDH systems under different design conditions. Aburub et al. [11,12] experimentally assessed the performance of another configuration of HDH system, which is described as a packed-bed cross-flow humidification-dehumidification desalination system. The system is a closed water (brine recirculation), and open-air configuration.

To enhance the performance of HDH desalination system, many modifications have been made. A novel HDH system driven by forced convection was invented by Brendel [13,14]. In this configuration, a forced convection was used to extract water from the dehumidifier and injected to the dehumidifier under balanced temperature profiles. Thermal balancing by extracting air or water from the humidifier and injected to the dehumidifier and vice versa has been investigated extensively by several researchers [15–21], all in an attempt to improve the performance of HDH system. From the above-cited work, we found that there is a need to systematically improve the cycle performance of HDH system by modifying the cycle. Therefore, the objective of this paper is to experimentally and analytically analyze the performance of a basic open-water open-air (OWOA) cycle and improve the cycle performance through a modified closed-water open-air cycle (CWOA). The modified closed-water open-air is achieved by incorporating heat recovery options.

2. System description and mathematical modeling

2.1. The basic cycle: open water open air (OWOA) HDH system

The basic cycle is an open-air and open-water loop as shown in Fig. 1. The seawater is passed through the dehumidifier and then heated in the heater before it is sprayed in the humidifier. A portion of sprayed hot saline water evaporates into the air stream, while the rest is rejected through the bottom of the humidifier, as a rejected brine. Air flows in a counter-flow direction through the packing material placed in the humidifier, where the air is heated and humidified through the direct contact with the sprayed hot water. The hot and humid air then flows to the dehumidifier where water vapor present in the humidified air condenses to produce fresh water, and the cold air is ducted out of the dehumidifier.

2.2. The modified closed-water open-air (CWOA) HDH system

The modified closed water open-air HDH System, as illustrated in Fig. 2, is similar to the basic cycle of open water open-air loop, except that the modification is made in the water loop. In Fig. 2, the saline water enters the dehumidifier and absorbs heat from the hot and humid air. A portion of the preheated saline water is admitted into a tank as a make-up water, while the rest is discharged. The saline water in the