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Exergo-economic analysis of a hybrid humidification dehumidification reverse osmosis (HDH-RO) system operating under different retrofits

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ABSTRACT

The paper presents an exergo-economic analysis of humidification-dehumidification (HDH) desalination system operating under a conventional open-water open-air (OWOA) and a modified closed-water open-air (CWOA) configuration. Besides, the possibility of coupling a reverse osmosis (RO) system with HDH unit is also analyzed. The hybrid HDH-RO system is studied under three different retrofits including a simple HDH-RO, HDH-RO with a Pelton turbine and HDH-RO with a pressure exchanger. The analysis reveals that the modified cycle has a higher exergetic efficiency and lower product cost than the basic cycle. The product cost for the basic cycle with an electrical heater is calculated to be \$6.56/m^3 and with the solar heater \$5.98/m^3. Moreover, it is observed that the hybrid HDH-RO system with a pressure exchanger has the highest gained output ratio and second-law efficiency followed by HDH-RO with a Pelton turbine and simple HDH-RO, respectively. The product cost for hybrid HDH-RO with a pressure exchanger is calculated to be \$0.13/m^3 and \$0.12/m^3 with an electrical and solar heater, respectively.

1. Introduction

About 40% of the world population is suffering from water scarcity issue which is expected to extend to almost 60% by 2025 [1] because of increasing population and limited fresh water access. Since the coastal areas are inhabited with a large percentage of world population, within 70 km of seashores [2], industrial desalination seems to be a very promising technique to handle water shortage. Meanwhile, the energy demand for producing the convenient amount of potable water is very high [3,4]. The conventional desalination systems mainly use fossil fuels as an energy source. The environmental impact of these sources accompanied with their unsustainable nature, urge the need to come up with more sustainable techniques [5].The conventional systems are still better in terms of efficiency and economic feasibility than sustainable desalination technologies. However, the desalination systems that use renewable energy have a good chance to outperform the conventional plants in the long term [6]. The problem of increasing the size of humidification-dehumidification (HDH) systems for commercial applications is mainly constrained by high energy consumption. This fact motivated the idea of hybridization with conventional desalination plants. A plenty of work in the literature was devoted to this issue [7–9]. For example, Nada et al. [10] investigated the performance of HDH system coupled with an air conditioning system. They studied many hybrid configurations and reported an increase in the amount of produced potable water when the supplied air temperature was increased.

In addition, Yildirim et al. [8] analyzed another type of hybrid system between HDH and thermoelectric cooling cycle. They developed a pilot plant to evaluate the performance of this integration and reported a potable water mass flow rate of 0.135 kg/day and the cooling unit coefficient of performance of 0.78. In an attempt to reduce the energy consumption, a hybrid HDH and reverse osmosis system has been proposed by Narayan et al. [7]. The GOR for this hybrid system was observed to be considerably higher (i.e., 20) than the traditional HDH systems. Likewise, another system integrating an air heated HDH with a single stage flash desalination system was studied [11]. The heat input was generated from a solar collector that used to heat both air and water [12]. The economic feasibility of this system was evaluated in a separate work [13]. They found that the hybrid system had a better productivity and was more economical than the standalone systems. Furthermore, Eslamimanesh et al. [14] compared a pilot HDH set-up to an RO system from an economic viewpoint. They suggested to couple HDH system with an RO to get the optimum performance. Recent studies have been focused on the integration of HDH systems with wastewater treatment plants [15–18]. This combination enables HDH to serve in a wide range of water process applications.

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Nomenclature

C	cost ($\$\,m^{-3}$)
$\dot{C}$	rate of cost ($\$\,s^{-1}$)
e	efficiency ratio, Eq. (19) $\left(\frac{\eta_{Component}}{1-\eta_{Component}}\right)$
h	enthalpy ($kJ\,kg^{-1}$)
i	interest rate
max	maximum
$\dot{m}$	mass flow rate ($kg\,s^{-1}$)
n	amortization period
P	pressure (kPa)
$\dot{Q}$	heat transfer (kW)
T	temperature (C)
$\dot{V}$	volumetric flow rate ($m^3\,s^{-1}$)
$\dot{W}$	power (kW)
x	the fraction of mass flow rate used as makeup
$\dot{X}$	exergy rate (kW)
y	the fraction of rejected brine mass flow rate recirculated to the tank
Z	fixed cost ($)
$\dot{Z}$	rate of fixed cost ($\$\,s^{-1}$)

Symbols

ε	effectiveness
η	efficiency
Δ	change in quantity
ω	absolute humidity

Subscripts

a	air
b	brine
D	destroyed
db	dry bulb
deh	dehumidifier
fg	latent
fw	freshwater
hum	humidifier
is	isentropic
p	pressure
PT	Pelton turbine
PX	pressure exchanger
w	water
wb	wet bulb
II	Second law

Abbreviations

CRF	capital recovery factor
CWOA	closed-water open-air
EES	engineering equation solver
GOR	gain output ratio
HDH	humidification-dehumidification
HPP	high pressure pump
MR	mass flow rate ratio
OAOW	open-air open-water
OM	operation and maintenance
RO	reverse osmosis
RR	recovery ratio
SEC	specific energy consumption ($kWh\,m^{-3}$)

The literature review indicates that the conventional HDH systems are energy intensive and there is a need to improve the performance of such systems, continuously. To add a value to the field of HDH desalination, the current study is focused to analyze and compare the performance of a modified closed-water open-air (CWOA) HDH system with the conventional open-air open-water (OAOW) HDH system from both the first- and second-law standpoints. Moreover, the study explores the possibility of coupling an RO with the basic cycle as an alternative to the brine recirculation system. In addition, three different retrofit options for an RO section are proposed and analyzed, which are first time introduced in the context of an HDH-RO coupled system. Finally, to complete the technical and economic evaluation for each of the retrofit options, the analysis is directed to look at the economic aspects of these systems.

2. Systems description and assumptions

The systems considered in the current analysis are given below.

2.1. Basic (OAOW) and modified (CWOA) HDH systems

The basic cycle (with 0 % brine recirculation) consists of an open-air and open-water loop, as shown in Fig. 1. The saline water is passed through the dehumidifier and then heated in the heater before spraying in the humidifier where it evaporates partially, and the rest is rejected as brine. The evaporated water is carried with the dry air coming from the blower and leaves the humidifier as hot humid air. This air is passed to the dehumidifier where it condenses, and the condensate water is collected as fresh water while the air leaves the system.

As illustrated in Fig. 2, CWOA (100% brine recirculation) system consists of the same components as the previous system. Unlike the original configuration, the water loop is closed in the modified system. The saline water enters the dehumidifier and absorbs heat from the hot humid air and then it is partially admitted to a tank as a makeup water and the rest is thrown away. The water from the tank is sprayed in the humidifier where it evaporates. The portion which is not evaporated is then collected and circulated back to the tank to close the water loop. The air loop is open and same as the previous system (see Fig. 1).

2.2. Hybrid/combined (HDH-RO) systems

Three RO systems are suggested being coupled with the OAOW HDH system as an alternative option to the circulation of rejected brine (the modified cycle). The rejected brine is utilized in an RO module with a pump which is the first option, as illustrated in Fig. 3. The pump will drive the saline water across the module to separate fresh and saline water as it passes through it. The second option is shown in Fig. 4 that is to equip the RO module with a Pelton turbine to recover the pressure energy of the rejected brine from the RO as an energy recovery unit. The recovered energy is utilized in the high-pressure pump. The other option is to equip the RO with a pressure exchanger to exchange the pressure from the high pressure rejected brine stream exiting the RO module and the rejected brine exiting the humidifier before it enters the high-pressure pump, as shown in Fig. 5.

The current analysis is based on the following assumptions: (a) steady-state conditions, (b) negligible heat loss in the components, (c) heat input is taken to be 4.5 kW, (d) properties are evaluated based on Sharqawy et al. [19]correlations, (e) air inlet temperature is at 26 °C and 50% relative humidity, (f) air leaves both the humidifier and dehumidifier at 90% relative humidity, (g) the feed water mass flow rate of 0.07 kg/s with a salinity 35 g/kg, (h) water inlet temperature is at 21 °C, (i) dead state for feedwater is taken at the condition of inlet