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Exergo-economic analysis of humidification-dehumidification (HDH) desalination systems driven by heat pump (HP)

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ABSTRACT

In this study, exergo-economic analysis of two layouts of humidification-dehumidification (HDH) desalination systems driven by a vapor compression heat pump (HP) is presented and discussed. The systems are closed-air open-water water-heated cycle coupled with a heat pump (HP-HDH-WH), and modified air-heated cycles integrated with a heat pump (HP-HDH-AH). For the purpose of comparison, a conventional closed-air open-water (CAOW) electric water heated HDH system (E-HDH-WH) is also presented. Exergy destruction, exergetic efficiency and product cost are evaluated for these systems. The influence of input parameters such as mass flowrate ratio, dehumidifier effectiveness, compressor isentropic efficiency, and feed water temperature on second-law efficiency and exergy destruction associated with the major components of the systems are analyzed. The impact of input cost parameters is investigated using two different approaches. The analysis shows that evaporator and compressor are the components with the largest exergy destruction. The exergy efficiency for the HP-HDH air-heated unit, HP-HDH water-heated unit, and E-HDH water-heated unit is found to be 1.097%, 0.06965% and 0.05795%, respectively. The cost of desalinated water evaluated by current analysis for HP-HDH air-heated system, HP-HDH water-heated cycle, and E-HDH water-heated unit is found to vary from 4.61$/m^3 to 5.49$/m^3, 6.00$/m^3 to 7.14$/m^3, and 4.44$/m^3 to 14.95$/m^3, respectively. The results generally reveal that HP-HDH air-heated cycle shows better performance both from energetic and exergetic viewpoints.

1. Introduction

Potable water demand is growing worldwide, due to the rising population, urbanization, industrialization, and, in some cases, agricultural activities, and socio-economic development [1]. In some arid and semi-arid areas, desalination remains the effective solution to address the water scarcity problem [2]. Desalination process produces potable/clean water from brackish or saline water. It is a reliable, economic and sustainable technical solution to address the persistent problem of the global water scarcity. Among several desalination technologies is the humidification dehumidification (HDH) desalination technology. HDH process is a promising thermal desalination technique that employs carrier gas to desalinate saline water. HDH desalination process is suitable for decentralized small scale and medium scale fresh water production. HDH systems are simple in design and easy to manufacture. It requires low maintenance, and can be operated by renewable or low-grade energy.

Different layouts of HDH cycles have been proposed to enhance the performance of HDH system. For instance, the performance of HDH system has been improved by balancing the humidifier/dehumidifier thermodynamically [3]. Aburub et al. [4] experimentally assessed the performance of a packed-bed cross-flow humidification dehumidification desalination system with a closed water (brine recirculation), open-air configuration. The performance of the same cross-flow HDH system was further improved by Lawal et al. [5] through multiple mass extractions and injections. The gained output ratio of the system was reported to have been increased by more than two fold through the mass balancing. The performance of HDH system has also been improved through the modification of its cycle. In this regard, Zubair et al. [6] performed an experimental and thermodynamic analysis of the energetic performance of a basic open-air open-water (OAOW) cycle and a modified closed-water open-air (CWOA) cycle with the options of brine recirculation. Their results indicated that 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.

One of the major setbacks of HDH desalination system is the high energy demands of the system. From a thermodynamic and environmental point of view, it is more appropriate to use waste heat to operate water purification systems than high-grade energy such as electricity,

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Nomenclature

Acronyms

HDH	humidification-dehumidification
HP	heat pump
E	electric heater
GOR	Gain Output Ratio
CAOW	closed air open water
MR	mass flowrate ratio
SEC	specific energy consumption (kWh/m^3)
C-F-M	cost flow method
E-E-M	El-Dessouky and Ettouney Method
COE	cost of electricity ($/kWh)

Symbols

h	enthalpy (kJ/kg)
h_{fg}	latent heat of vaporization (kJ/kg)
P	pressure (kPa)
T	temperature (K)
$\dot{m}$	mass flow rate (kg/s)
C_p	specific heat capacity at constant pressure (kJ/kg·K)
$\dot{Q}$	heat transfer rate (kW)
$\dot{W}$	power (kW)
$\dot{V}$	volumetric flowrate (m^3/h)
$\dot{X}$	exergy rate (kW)
Z	capital costs ($)
$\dot{Z}$	rate of fixed charges ($/yr)
n	plant life expectancy
$\dot{A}$	plant availability
$\dot{c}$	cost rate ($/s)
c	product cost ($/m^3)

Greek letters

ε	effectiveness
ω	humidity ratio
μ	chemical potential
w_s	mass fraction
η	efficiency
β	fuel depletion ratio
χ	relative irreversibility
δ	productivity lack
ξ	exergetic factor
Γ	improvement potential
$\mathscr{L}$	specific cost of operating labor
α	amortization factor
$	US dollars

Subscripts

a	air
b	brine
w, sw	water
fw	fresh water
in	entering/output
out	intput/exiting
r	refrigerant
1, 2, 3, …	state points
II	second law
Evap	evaporator
Comp	compressor
cond	condenser
EXV	expansion valve
dest	destroyed
H, hum	humidifier
D, dehum	dehumidifier
FP	feed pump
Elect	electricity
f	fixed charges
L	labor cost
T	total
mt	maintenance
mg	management
p	product

oil or natural gas with its associated environmental pollution. The lower the temperature of heat source, the lesser its work equivalent or exergy and consequently its economic value [7]. Several innovative ideas have been proposed in an attempt to reduce the energy consumption of HDH systems. Nada et al. [8] investigated the performance of hybrid HDH system coupled with an air conditioning system. The system provides fresh water, as well as thermal comfort requirements of a conditioned space. Gao et al. [9] performed an analysis on a new type of desalination unit consisting of a heat pump coupled with an air-heated HDH system. The solar photovoltaic system was embedded in the HDH system to support the heating process. Recently, Lawal et al. [10] analyzed two different layouts of HDH systems driven by a mechanical vapor compression heat pump system. Mass and energy analysis was performed to determine the performance of the combined system. Their systems were reported to attain a maximum GOR of 8.88 and 7.63 for the modified air heated cycle and water heated cycle, respectively. The system was also reported to achieve a GOR > 10 at certain conditions.

Thermodynamic analysis, particularly exergy analysis appears to be an essential tool for system design analysis and optimization. The exergy analysis concept is widely recognized as a necessary tool to quantify the thermodynamic losses in a given system [11]. Through Second Law analysis, the minimum work required to drives an HDH desalination system has been estimated by Alhazmy [12]. The author performed an energy and exergy analysis to quantify the effective utilization of energy in the modified HDH desalination system.The irreversibility analysis has also been applied by Mistry et al. [13] to characterize HDH desalination cycles and identified ways to improve the HDH cycles and its components. Al-Sulaiman et al. [14] performed exergy analysis on a proposed hybrid TVC–HDH–RO (humidification dehumidification system coupled with reverse osmosis operated by thermal vapor compressor) desalination system and introduced new performance parameter called the total true specific exergy lost. The new parameter was found to be useful in assessing the exergetic performance of the considered system. Ashrafizhadeh and Amidpour [15] performed an exergy analysis on a HDH system and developed equations for exergy analysis of the system. The model developments involved a sink and source model, as well as basic relations characterizing the system.

Besides exergy analysis, another useful way of analyzing desalination systems is through exergo-economic analysis, which combines exergy analysis with cost by calculating the exergetic as well as the monetary cost of each stream in the system. Jamil et al. [16] presented an exergo-economic analysis of HDH desalination system of the following configurations; a basic open-water open-air (OWOA) and a modified closed-water open-air (CWOA) configuration. The analysis was extended by coupling an HDH unit with reverse osmosis (RO) system having different retrofit options. Their results show that the modified cycle has the higher exergetic efficiency and lower product cost ($2.82/m^3) when compared to the basic cycle ($6.56/m^3). A low product cost of $0.13/m^3 was achieved from the integrated HDH-RO