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A mechanical vapor compression desalination system coupled with a transcritical carbon dioxide Rankine cycle

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ABSTRACT

In this paper, a desalination system in accordance with the running principles of mechanical vapor compression (MVC), in which the steam compressor is driven by a transcritical carbon dioxide (CO_2) Rankine cycle (CRC), is suggested. The integrated mechanisms between the two subsystems are revealed and analyzed through the corresponding mass and energy conservation. The turbine parameters, comprising the inlet pressure and temperature, are first specified to explore the relevant influence impacts, and the obtained results are applied to accomplish the sensitivity analysis focusing on the top temperature of the seawater boiler, ambient temperature and terminal temperature difference (TTD) of the MVC heater. In combination with the entropy generation values of the components both within the MVC and CRC subsystems, all the calculated results are sufficient to prove the practicability and availability of the combined desalination system, producing freshwater. It is found peak values of the freshwater production, $m_c = 1.29\ \text{kg s}^{-1}$ and gained output ratio (GOR), GOR = 2.42, arise at the prescribed parameter range. Based on the results from the sensitive analysis, it is found a more prominent freshwater production and energy conversion efficiency can result from a higher top temperature, a lower ambient temperature and TTD of the MVC heater. Furthermore, based on the detailed simulations for the heat exchanger configurations, it is obtained that the total heat transfer area arrives at $A_t = 381.54\ \text{m}^2$ at $T_t = 353.15$ K, with a total cost of $C_t = 212{,}040.86$¥.

1. Introduction

As a result of the serious water contamination from the industry development all over the world, water crisis, especially for the potable water, has become reality. Therefore, desalination methods to produce freshwater have been paid a great amount of attention during the past decades. Generally, the existing desalination systems can be distinguished as the thermal and membrane version [1,2]. The thermal desalination systems can be powered through heat or mechanical energy, and multi-effect evaporation (MEE) [3], multi-stage flash (MSF) [4], thermal vapor compression (TVC) [5] and humidification-dehumidification (HDH) [6], while the driving force of the desalination system based on mechanical vapor compression (MVC) comes from mechanical energy to impulse the steam compressor [7].

Helal [8] structured and focused on a novel diesel solar-assisted MVC desalination cycle in the remote regions to relieve the water scarcity in the UAE, with a freshwater production of 120 m^3/day. In such desalination configuration, a photovoltaic array was installed to work as the power supplier, driving the steam compressor. Moreover, the main expense to construct the desalination plant was also focused based on the sensitive analysis for the design parameters. Taking the CO_2 emission and oxygen consumption as the objective, the environmental impacts resulted from the solar-assisted desalination unit was also evaluated. An optimized design method for the MVC desalination processes was researched and exhibited by Marcovecchio [9]. According to confirm the optimal design method and the relevant working conditions for the MVC cycle, detailed mathematical models and a global optimization process were suggested. In the light of the chemical and physical properties, nonlinear equations were used to describe the evaporation principles. Furthermore, the previous mathematical models were solved under the appointed seawater conditions with different salinity, temperature and freshwater flow rate. A MEE–MVC coupled desalination thermal cycle was also constituted by Nafey [10], and a water production of 1500 m^3/day can obtained. Exergy and thermo-economic analysis on the basis of the relevant mathematical models were studied. It was observed compared to the case with

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Nomenclature

Roman symbols

A	heat transfer area (mm^2)
b	channel height (mm)
C	cost (¥)
D	diameter (mm)
f	friction factor
g	acceleration of gravity ($m\ s^{-2}$)
h	enthalpy ($kJ\ kg^{-1}$); convective heat transfer coefficient ($W\ m^{-2}\ K^{-1}$)
h_{fg}	latent heat ($kJ\ kg^{-1}$)
k	thermal conductivity ($W\ m^{-1}\ K^{-1}$)
m	mass flow rate ($kg\ s^{-1}$)
Nu	Nusselt number
p	pressure (MPa)
P_r	Prandtl number
Q	heat capacity (kW)
Re	Reynolds number
s	specific entropy ($kJ\ kg^{-1}\ K^{-1}$)
ΔT_{LMTD}	logarithm mean temperature difference (K)
S	concentration of seawater ($g\ kg^{-1}$); entropy rate ($kW\ K^{-1}$)
T	temperature (K)
U	overall heat transfer coefficient ($Wm^{-2}\ K^{-1}$)
W	power (kW); channel width (mm)

Greek letters

β	plate chevron angle (°)
Δ	plate thickness (mm)
ρ	density ($kg\ m^{-3}$)
μ	dynamic viscosity($kg\ m^{-1}\ s^{-1}$)
φ	condensate discharge angle (°)

Subscripts

b	brine
c	compressor; cold
con	condenser
cb	CO_2 boiler
ci	compressor inlet
co	compressor outlet
CO_2	carbon dioxide
CRC	CO_2 Rankine cycle
f	film
h	heater, hot
i	inlet; inside
HE	heat exchanger
LGWH	low grade waste heat
MVC	mechanical vapor compression
MVR	mechanical vapor recompression
o	outlet; outside
p	pump
pA	preheater A
pB	preheater B
PHE	plate heat exchanger
PCHE	printed circuit heat exchanger
s	seawater
sb	seawater boiler
t	turbine; top
w	water

external steam, the performance ratio for the desalination system without external steam is 8% higher. According to the simulated results from the thermo-economic analysis, the unit production cost was discovered to be 29% higher at the case of external steam.

As a matter of fact, in addition to produce freshwater in the desalination thermal cycle, MVC was also applied in the field of evaporative crystallization for recovery of crystal from solution [11,12], always called mechanical vapor recompression (MVR). Han [13] raised two MVR thermal cycles to retrieve ammonium sulfate, and the corresponding mass and energy conservation laws were simulated and shown. Compared to the conventional three effect evaporation process, a more prominent performance for the current system was found and the relevant reasons were revealed. Furthermore, between the two MVR systems, a maximum reduction amplitude reaching 40% for the double-stage MVR system was obtained.

It has been mentioned the MVC method belonged to the power driven type, and it is applicable for the occasions with enough power or electricity to drive the steam compressor, and thus the pressurized steam can be used to evaporate the supplied seawater or solution in the heater. Nevertheless, the driving force is not always available, and enough power should be first produced. Seeing that the serious environmental problems originated from the combustion of the fossil fuel, the low grade waste heat and renewable energy attracted more and more attentions to elevate the energy conversion efficiency and avoid pollution. The concept of transcritical CO_2 Rankine cycle [14–16] was investigated and put into reality extensively, which showed more advantages to be coupled with low grade waste heat or renewable energy [17]. A transcritical CO_2 thermal system to produce electricity was presented by Wang [18], taking geothermal energy as the heat sources, and liquefied natural gas (LNG) was employed as the cooling fluid to decline the turbine back pressure. Based on the mathematical model for the steady-state problem, the parametric analysis was achieved to assess the influences from several critical thermodynamic parameters on the performance of the thermal system. Furthermore, a multi-objective optimization method was also applied to discover the optimal performance. It was found there exists an optimal CO_2 turbine inlet pressure corresponding to the maximum exergy efficiency, and a higher CO_2 turbine inlet temperature or a lower CO_2 turbine back pressure will contribute to a higher exergy efficiency. Banik [19] introduced a parametric optimization method to a transcritical carbon dioxide power cycle, in which part of the CO_2 mass flow was recompresses before entering the precooler to release the potential for a higher efficiency. Garg [20] accomplished a quantitative methodology for load regulation within a CO_2 Brayton cycle to calculate the thermal efficiency and specific work output. The analysis results told that a transcritical CO_2 system is more flexible under part load case compared to the supercritical one in non-solar power plants, while supercritical CO_2 version is better than the transcritical CO_2 cycle in the concentrated solar power.

According to the forementioned literature survey, it can be generalized that a coupled system based on the MVC and CO_2 thermal cycle will be a novel concept to desalinate seawater or brackish water. Due to the power demand to achieve the mechanical compression, it is innovative to utilize the low grade waste heat or renewable energy as the heat resources overcoming the power-starved occasions in many countries. In the present paper, a novel integration desalination system, with the mechanical vapor compression and a transcritical CO_2 Rankine cycle coupled, is constituted and analyzed. Mathematical models both for the MVC and CO_2 Rankine cycle according to the mass and energy conservation as well as entropy equilibrium, are illustrated, and then the corresponding thermal performance at the prescribed turbine inlet pressure and temperature is analyzed, with the feasibility validated. Furthermore, based on the foregoing results, top temperature at the