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Research Paper

Thermo-economic comparison of three configurations of combined supercritical CO_2 refrigeration and multi-effect desalination systems

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HIGHLIGHTS

- Three configurations of combined desalination and refrigeration systems are proposed and compared thermo-economically.
- The parametric study with thermodynamic and economic optimization is carried out.
- The optimizations results showed that the most change is associated to recovery ratio.
- Despite TSC, expander modification presents high COP and RR simultaneously.
- The highest and lowest exergy efficiency belongs to evaporator and MED respectively.

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ABSTRACT

This paper proposed a novel combination of the supercritical carbon dioxide refrigeration and Boosted-multi-effect-desalination system. Comparative study of the combined system and two different modifications of it is performed from thermo-economic viewpoint. Thermodynamic and economical optimization is also carried out for the two modified forms; equipped with the expander and two-stage compression. It is found that an acceptable recovery ratio is gained from the introduced system compared to that of the conventional steam-driven MED. For both modifications, thermodynamic optimization results showed that COP and exergy efficiency improve about 12% and 8% respectively, at the expense of 18% increment in the TAC rate, compared to the optimal economical design case. On the other hand, the most enhancement resulted from the thermodynamic optimization was associated with the case in which the recovery ratio was increased up to 200% compared to that of the economical one. However, the TAC rate for the two compressors modification is 2.2% lower than that of the expander one. While, the first modification would significantly decreases the recovery ratio (about 41%). Finally, by the exergo-economic factor definition, a reasonable decision about the stability between the exergy destruction of the components and their capital investment would be achieved.

1. Introduction

The world encounters a great challenge of providing water and cooling. The demand has grown up drastically, while the water and energy sources are limited and running out. Although the need for these two products usually coincides in many regions, they are produced separately. The high cost rates to produce fresh water and cooling demand separately and the significant amount of waste heat from these two systems lead to serious negative impacts on the environment and climate area. Enormous attempts are performed to make the energy use more efficient, sustainable, cost effective, commercially viable and clean. Therefore, the cogeneration issue, as a method of minimizing waste energy and increasing efficiency, has become a potential option and solution to current energy and environmental crises.

Carbon dioxide as a refrigerant is non-flammable, non-toxic, cheap and has a high volumetric refrigeration capacity, but the COP of the HVAC & R systems based on CO_2 are not commercially competitive. This is because of the high pressure ratio that should be provided by the compressor and the large thermodynamic losses especially associated with throttling process in the expansion valve [1,2]. Sub-cooling, multi-staging and power recovery by utilizing an expander are known as effective solutions to its thermodynamic and commercial success [2]. In such a way, Shariatzadeh et al. [3] have compared four different configurations of

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Nomenclature

BPE	boiling point elevation (°C)
COP	coefficient of performance
Cp	specific heat (kJ/kg/K)
c	unit cost of exergy ($ kW h^{-1})
$\dot{C}$	cost rate ($ h^{-1})
D	distillate production rate (kg/s)
d_i	inner diameter of CO_2 tube (mm)
d_o	outer diameter of CO_2 tube (mm)
e	specific exergy (kJ/kg)
EES	equation engineering solver
$\dot{Ex}(\dot{E})$	exergy rate (kW)
h	specific enthalpy (kJ/kg)
h_{fg}	latent heat (kJ/kg)
HPC	high pressure compressor
LPC	low pressure compressor
$\dot{m}$	mass flow rate (kg/s)
m	capacity of the MED plant (m^3/day)
Nu	Nusselt number
Pr	Prandtl number
P	pressure (kPa)
PF	plant load factor
$\dot{Q}$	net heat transfer rate (kW)
s	specific entropy (kJ/kg K)
T	temperature (°C)
TBT	top brine temperature (°C)
v	specific volume (m^3/kg)
$\dot{W}$	net consumed power (kW)
w (or *x*)	salinity (g/kg)
$\dot{Z}$	capital cost rate ($ h^{-1})
Z	capital cost ($)

Subscripts

0	reference state
amb	ambient
B	booster
Br	brine
CO_2	carbon dioxide
cm	cooling medium
com	compressor
cw	cooling water
eva	evaporator
elec	electrical
Ex. valve	expansion valve
Exp	expander
GAC	gas-cooler
in	inlet
$\dot{m}$	mass flow rate (kg/s)
mec	mechanical
out	outlet
P_{com}	compressor outlet pressure
Ref	refrigeration
RR	recovery ratio (%)
supply	supplied to the system
sw	seawater
vs	vapor saturation
w	water

Greek

η_{ex}	second law efficiency (exergy efficiency)
η_{mec}	mechanical efficiency
η_{elec}	electrical efficiency
μ	chemical potential
λ	thermal conductivity (W/(m K))

CO_2 refrigeration system from the aspect of COP and exergy gain. Mohammadi and Ameri [4] have also studied different configurations of an absorption-two-stage compression cascade refrigeration system with Carbon Dioxide refrigerant in order to introduce the most effective one.

Among different thermal desalination systems, MED has been more interesting than Multi-Stage-Flash (MSF); because of lower corrosion rate, less power consumption and lower desalted water costs [5,6]. Its reliability and robustness to fouling make it a desired choice to produce fresh water [7]. Gude [8] have offered a MEE-ABHP (Multi effect evaporation-Absorption heat pump) combinational system, in which the rejected absorption heat is the energy source of water treatment system. Dincer et al. [9], proposed a thermodynamic model of the combination of micro gas turbine cycle and solid oxide fuel-cell with the MED, equipped with thermal vapor compression.

In order to supply useful information on cost effective energy conversion systems and correctly evaluates the real costs of energy sources, the exergo-economic analysis which combines the principles of thermodynamics and economics, can be carried out. In general, the exergo-economic analysis was used to identify the cost formation processes and to calculate the cost exergy unit of the product streams of the system through the conventional energy and economic modeling [10]. Nafey et al. [11] used an existing MEE–MVC (Multi effect evaporation-Mechanical vapor compression) plant and investigated the influences of various operating parameters on the investment costs of the overall systems and on the product cost flow rates. Farshi et al. [12], represent a comparison between two configurations of absorption cascade refrigeration system from exergo-economic viewpoint. Esfahani et al. [13] applied the thermo-economic model of MED-ABHP system to evaluate the unit cost of the fresh water and cooling. They also assessed the flexibility of the system for fuel, from different sources of electricity and heat energy.

In this study three new configurations of a combined system, consists of MED/CO_2 refrigeration with expansion valve (base system), MED/CO_2 refrigeration with expander and MED/CO_2 refrigeration with two stage compression (TSC) are analyzed and compared from thermodynamic and economic viewpoints. Also, supercritical CO_2 system is introduced as a novel heat source medium for MED system and its heat transfer characteristics are investigated. The energy analysis does not assume any distinction between work and heat, does not offer any information related to the optimum energy conversion and cannot specify the sources of dissipation. So, the primary objective of this research is the comprehensive exergoeconomic analysis in order to calculate the cost formation processes and to determine the cost exergy unit of the product streams of each component of the suggested systems. Also a thermodynamic and economic optimization is performed, based on maximum exergy efficiency and the minimum total cost rate respectively, in order to specify the performance parameters that change the most due to optimization processes.

2. System description

Fig. 1 illustrates a schematic diagram of the proposed base combined system. This system is consisted of a CO_2 supercritical refrigeration system a booster module and a basic MED system with 6