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Exergoeconomic and environmental analyses of CO_2/NH_3 cascade refrigeration systems equipped with different types of flash tank intercoolers

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ABSTRACT

Exergoeconomic and environmental analyses are presented for two CO_2/NH_3 cascade refrigeration systems equipped with (1) two flash tanks and (2) a flash tank along with a flash intercooler with indirect subcooler. A comparative study is performed for the proposed systems, and optimal values of operating parameters of the system are determined that maximize the coefficient of performance (COP) and exergy efficiency and minimize the total annual cost. The operating parameters considered include condensing temperatures of NH_3 in the condenser and CO_2 in the cascade heat exchanger, the evaporating temperature of CO_2 in the evaporator, the temperature difference in the cascade heat exchanger, the intermediate pressure of the flash tank in the CO_2 low-temperature circuit, the mass flow rate ratio in the flash intercooler and the degree of superheating of the CO_2 at the evaporator outlet. The total annual cost includes the capital, operating and maintenance costs and the penalty cost of GHG emission. The results show that, the total annual cost rate for system 1 is 11.2% and 11.9% lower than that for system 2 referring to thermodynamic and economic optimizations, respectively. For thermodynamic and cost optimal design condition the COP and exergy efficiency of both systems are almost the same. Finally, in order to obtain the best balance between exergy destruction cost and capital cost, the exergoeconomic factor is defined for each component of proposed systems, for cases in which the system operates at the best performance conditions.

1. Introduction

The use of CO_2 as a working fluid in refrigeration cycles has expanded notably in recent years, because it has low global warming potential (GWP) and no ozone depletion potential (ODP). It is also non-flammable, inexpensive and abundant in nature. Moreover, CO_2 (R744) has advantages in use as a refrigerant in low temperature applications such as storage of frozen food and rapid freezing systems. Despite of these advantages of CO_2 as a working fluid in refrigeration cycles, using carbon dioxide as the working fluid in a single stage refrigeration cycle is normally not economical due to the high pressure difference between evaporator and condenser. In single stage refrigeration systems using CO_2 as a refrigerant, a high pressure ratio and condensation close to the critical conditions lead to a low coefficient of performance (COP) in comparison with the refrigeration cycles working with HFC refrigerants [1].

Two-stage compression systems and cascade refrigeration cycles can be used for these applications to overcome the aforementioned problem [2–7]. A cascade refrigeration cycle involves two refrigeration circuits which are thermally coupled through an internal cascade heat exchanger. The internal cascade heat exchanger plays the role of condenser for the low temperature circuit and evaporator for the high temperature circuit. The CO_2/NH_3 cascade refrigeration cycle uses two natural refrigerants, NH_3 (R717) in the high temperature circuit and CO_2 in the low temperature circuit, and is a well-known system in refrigeration industry.

Research on CO_2/NH_3 cascade refrigeration has been reported by several authors. Lee et al. [8] thermodynamically assessed a CO_2/NH_3 cascade refrigeration to determine the optimal condensing temperature of the cascade heat exchanger to maximize the COP and minimize the exergy destruction of the system. Getu and Bansal [9] thermodynamically analyzed a CO_2/NH_3 cascade

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Nomenclature

A	area (m^2)
c	unit cost of exergy ($\$ \, kJ^{-1}$)
$\dot{C}$	cost rate ($\$ \, s^{-1}$)
CO_2e	carbon dioxide equivalent
COP	coefficient of performance
CRF	capital recovery factor
E	electrical energy consumption (kW h)
$\dot{E}x$	exergy rate (kW)
f	exergoeconomic factor
F	correction factor
FT	flash tank
FIS	flash intercooler with indirect subcooler
GHG	greenhouse gas
GWP	global warming potential
h	specific enthalpy ($kJ \, kg^{-1}$)
HTC	high-temperature compressor
i	annual interest rate
LTC	low-temperature compressor
$\dot{m}$	mass flow rate ($kg \, s^{-1}$)
m	mass (kg)
n	system life time (year)
N	operational hours in a year (h)
ODP	ozone depletion potential
P	pressure (kPa)
PR	pressure ratio
$\dot{Q}$	heat rate (kW)
r	mass flow rate ratio
s	specific entropy ($kJ \, kg^{-1} \, K^{-1}$)
T	temperature (°C or K)
TV	throttling valve
ΔT_{lm}	logarithmic mean temperature difference (K)
U_o	overall heat transfer coefficient ($W \, m^{-2} \, K^{-1}$)
$\dot{V}$	volumetric flow rate ($m^3 \, s^{-1}$)
$\dot{W}$	electrical power (kW)
$\dot{Z}$	capital cost rate ($\$ \, s^{-1}$)
Z	capital cost ($)

Greek symbols

α_{el}	unit electricity cost ($\$ \, kW \, h^{-1}$)
ϕ	maintenance factor
η	energy efficiency
μ_{CO_2e}	emission conversion factor ($kg \, kW \, h^{-1}$)
ψ	exergy efficiency

Subscripts

0	ambient
ca	cooled air
CAS	cascade heat exchanger
CD	condenser
CM	compressor
D	destruction
e	exit
env	environment
el	electricity
EV	evaporator
F	fuel
i	inlet
int	intermediate
k	*k*th component
m	mechanical
OP	operation
P	product
s	isentropic
sup	superheating
t	thermal

refrigeration system and optimized several cycle operating parameters: condensing, evaporating, subcooling and superheating temperatures and temperature difference in the cascade heat exchanger. They showed that an increase in subcooling before expansion to the evaporator increased the COP of the system while an increase in superheating and condensing temperature decreased the COP. Dopazo et al. [10] analyzed a CO_2/NH_3 cascade refrigeration system and identified the optimum CO_2 condensing temperature based on energy and exergy points of view. Bingming et al. [11] experimentally investigated the effects of operation parameters on the performance of a CO_2/NH_3 cascade refrigeration system, and showed that the system COP is greatly affected by evaporating and condensing temperatures and temperature difference in cascade heat exchanger while it is only slightly sensitive to the degree of superheating. Dopazo and Fernández-Seara [12] experimentally evaluated a CO_2/NH_3 cascade refrigeration system for an industrial freezer with a −50 °C evaporating temperature. They also investigated the influence of the operating parameters on system performance and compared the results with those for common NH_3 two stage refrigeration systems under the same operating conditions. They concluded that the COP of the cascade system is similar to the COP of an ammonia double stage with intercooler and about 20% higher when an economizer is applied. Ma et al. [13] thermodynamically analyzed a CO_2/NH_3 cascade refrigeration system using a falling film evaporator–condenser as the cascade heat exchanger, and showed that the use of such a heat exchanger improved the system COP by providing a smaller temperature difference.

After a technical feasibility study, the thermodynamic analysis must be completed with considerations about the costs of systems incorporated. Therefore, an economic analysis should also be considered for analyzing a refrigeration plant. Mitishita et al. [14] developed an optimization methodology to reduce power consumption and costs for frost-free refrigerators. This methodology was used to determine the compressor size and efficiency, the number of condenser and evaporator fins and the evaporator air flow rate in order to minimize energy consumption. Various studies based on exergy and thermoeconomic concepts in relation to heat pumps [15–17] and refrigeration systems have been previously published. Rezayan and Behbahaninia [18] presented a thermoeconomic optimization for a simple CO_2/NH_3 cascade refrigeration system without considering environmental analysis. They investigated the influence of design parameters on total annual cost of the system when ambient temperature, cooling capacity and cold space temperature are constraints.

Exergoeconomic analysis plays a key role in determining the optimal performance of a thermodynamic system. By combining exergy analysis and economic principles in a cost-effective method, exergoeconomic analysis can be used to identify the optimum system design via exergy-aided cost minimization. Moreover, due to the consumption of fossil fuels to generate electricity, an environmental analysis that determines the amount