Energy Conversion and Management 148 (2017) 360–377

Contents lists available at ScienceDirect

Energy Conversion and Management

journal homepage: www.elsevier.com/locate/enconman

Energy, exergy and exergoeconomic analyses of a combined supercritical CO_2 recompression Brayton/absorption refrigeration cycle

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ARTICLE INFO

Article history:
Received 4 January 2017
Received in revised form 14 May 2017
Accepted 18 May 2017

Keywords:
Supercritical CO_2 recompression Brayton cycle
Absorption refrigeration cycle
Exergoeconomic analysis
Parametric analysis
Optimization

ABSTRACT

Exergoeconomic analysis is performed for a novel combined SCRB/ARC (supercritical CO_2 recompression Brayton/absorption refrigeration cycle) in which the waste heat from the SCRBC is recovered by an ARC for producing cooling. Parametric analysis is conducted to investigate the effects of the decision variables on the performance of the SCRB/ARC cycle. The performances of the SCRB/ARC and SCRBC cycles are optimized and compared from the viewpoints of first law, second law and exergoeconomics. It is concluded that combining the SCRBC with an ARC can not only enhance the first and second law efficiencies of the SCRBC, but also improve the exergoeconomic performance. The results show that the largest exergy destruction rate occurs in the reactor, while the components in the ARC have less exergy destruction. The reactor and turbine are the first and second important components from exergoeconomic aspects. When optimization is based on the exergoeconomics, the first and second law efficiencies and the total product unit cost of SCRB/ARC are 26.12% higher, 2.73% higher and 2.03% lower than those of the SCRBC. The optimization study also reveals that an increase in the reactor outlet temperature can enhance both thermodynamic and exergoeconomic performances of the SCRB/ARC. For the basic design case, the SCRB/ARC can produce 71.76 MW of the cooling capacity and 6.57 MW of the cooling exergy at the expense of only 0.36 MW of power in comparison with the SCRBC.

1. Introduction

Many efforts have been devoted to the high efficiency and the cost reduction of electricity generated by the nuclear power plants toward the successful future utilization of the nuclear power [1]. In recent years, the Gas Turbine-Modular Helium Reactor (GT-MHR) [2–6] and the supercritical CO_2 recompression Brayton cycle (SCRBC) [7–11] have become the advanced technologies in utilizing the nuclear energy. Compared with the GT-MHR, the SCRBC has a reasonable efficiency of 45.3% at a lower reactor outlet temperature of 550 °C, while the GT-MHR obtains a comparable efficiency at a significantly higher reactor outlet temperature of 850 °C [8]. The SCRBC proves to be a more promising approach of the energy utilization for the future power plants because of its compactness, simplicity, better economic aspect and higher efficiency. For the SCRBC, the compressor work can be significantly reduced by using the drastic changes of the CO_2 properties near the critical point, leading to a significant increase in the efficiency. It is known that the working fluid should be cooled to some temperature before the compression process. For the SCRBC, CO_2 is usually cooled to about 32 °C near its critical temperature (31.1 °C), which leads to a reasonable low-grade thermal energy (about 50% of the input energy) rejected to the pre-cooler [11,12]. Therefore the performance of the SCRBC can be improved by reutilizing the low-grade thermal energy in the pre-cooler through various waste heat recovery systems.

Much attention has been focused on the utilization of the waste heat from the SCRBC by using the organic Rankine cycles (ORCs). Besarati and Goswami [13] implemented a thermodynamic analysis and comparison of three different SCB/ORC (sunpercritical CO_2 Brayton/organic Rankine cycle) cycles. The results presented that the largest efficiency increment was obtained by adopting a simple SCBC (supercritical CO_2 Brayton cycle) configuration as the topping cycle. However, the maximum efficiency of the overall system was achieved by the SCRB/ORC (supercritical CO_2 recompression Brayton/organic Rankine cycle) cycle. Akbari and Mahmoudi [14] investigated a combined SCRB/ORC by using the exergy and exergoeconomic analyses. They concluded that the exergy efficiency of SCRB/ORC was higher than that of the SCRBC by up to 11.7% and that the total product unit cost of SCRB/ORC was lower than that of the SCRBC by up to 5.7%. Wang et al. [15] conducted a

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http://dx.doi.org/10.1016/j.enconman.2017.05.042
0196-8904/

Nomenclature

A	heat transfer area (m^2)
$\dot{C}$	cost rate ($/h)
c	cost per unit exergy ($/GJ)
$c_{P,tot}$	total product unit cost ($/GJ)
$\dot{E}$	exergy rate (kW)
e	specific exergy (kJ/kg)
f	exergoeconomic factor (%)
h	enthalpy (kJ·kg^{-1})
i_r	interest rate
LMTD	logic mean temperature difference (°C)
m	mass (kg)
$\dot{m}$	mass flow rate (kg·s^{-1})
M	molar mass (kg/kmol)
n	number of operation year
NK	number of system components
NP	number of system products
P	pressure (MPa) & (kPa)
PRc	compressor pressure ratio
$\dot{Q}$	heat transfer rate (kW)
r	relative cost difference (%)
s	entropy (kJ·kg^{-1}·K^{-1})
T	temperature (°C)
U	overall heat transfer coefficient (W·m^{-2}·K^{-1})
$\dot{W}$	power (kW)
x	recompressed mass flow ratio
X	ammonia concentration (%)
Z	capital cost of a component ($)
$\dot{Z}$	capital cost rate ($/h)

Greek letters

η	efficiency (%)
ε	effectiveness
γ	maintenance factor
τ	annual plant operation hours (h)
ΔT	temperature difference (°C)

Subscripts and abbreviations

0	dead (ambient) state
1,2, et al.	state points
abs	absorber
c	cooling
ch	chemical exergy
CI	capital investment
COD	cost optimal design
cold	cold end
com	compressor
con	condenser
COP	coefficient of performance
core	reactor core
CRF	capital recovery factor
D	destruction
EEOD	exergy efficiency optimal design
EUF	energy utilization factor
EUFOD	energy utilization factor optimal design
EV	expansion valve
ex	exergy
eva	evaporator
F	fuel
gen	generator
hot	hot end
HTR	high temperature recuperator
in	inlet
L	loss
LTR	low temperature recuperator
m	motor
mc	main compressor
OM	operation and maintenance
P	product
pc	pre-cooler
ph	physical exergy
pum	pump
R	reactor
rc	recompression compressor
ref	reference value
SHE	solution heat exchanger
sys	system
th	thermal
tot	total
tur	turbine
TV	throttling valve

comparative study between the SCRB/ORC and SCRB/CDTPC (supercritical CO_2 recompression Brayton/CO_2 transcritical power cycle) considering the exergy and exergoeconomics. The results showed that the second law efficiency of the SCRB/CDTPC cycle was comparable with that of the SCRB/ORC cycle. Meanwhile, the total product unit cost of the SCRB/CDTPC was slightly higher than that of the SCRB/ORC. Sánchez et al. [16] studied the performance of SCB/ORC with different pure organic fluids and hydrocarbon mixtures as working fluids in the bottoming ORC cycles. The results indicated that the overall efficiency of the SCB/ORC was 7% higher than that of the simple SCBC when the hydrocarbon mixtures were utilized in the bottoming ORC. Zhang et al. [17] simulated and analyzed a SCRBC combined with an ORC with liquefied natural gas as heat sink. They found that the overall thermal efficiency of the SCRB/ORC could be up to 52.12% under the operating conditions of 20 MPa, 800 K and part-flow ratio 6.8.

A number of studies have also been published on the utilization of the waste heat from the SCRBC by employing a CO_2 transcritical power cycle (CDTPC). Yari and Sirousazar [18] investigated the performance of the combined SCRB/CDTPC cycle. They found that the second law efficiency of the SCRB/CDTPC was 5.5–26% higher than that of the single SCRBC. Wang et al. [19] conducted a thermo-economic analysis on the performance of the SCRBC combined with a CDTPC. The results showed that the capital cost per net power output was 6% higher than that of the single SCRBC. Wang et al. [20] also carried out the thermodynamic comparison and optimization of two different configurations of supercritical CO_2 Brayton cycles with a bottoming CDTPC. They concluded that the thermal efficiencies of the recompression and simple configurations of the supercritical CO_2 Brayton cycles could be increased by 10.12% and 19.34%, respectively by adding a CDTPC. Wu et al. [21] performed a detailed analysis on a cooling and power system combining SCRBC with a CDTPC using liquefied natural gas (LNG) as the heat sink. The results revealed that the thermal efficiency of the SCRB/CDTPC could be achieved as high as 54.47% using LNG as heat sink.

Some investigations have also been performed on the recovery of the waste heat from the SCRBC by adopting a Kalina cycle. Li et al. [22] conducted an exergoeconomic analysis and optimization of a SCRBC coupled with a Kalina cycle. They reported that the total product unit cost and the exergy efficiency of the SCRB/KC (supercritical CO_2 recompression Brayton/Kalina cycle) were 5.5% lower and 8.02% higher than those of the SCRBC cycle. Mahmoudi et al. [23] also investigated a combined SCRB/KC from the viewpoints