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Exergoeconomic analysis and optimization of a combined supercritical carbon dioxide recompression Brayton/organic flash cycle for nuclear power plants

Chuang Wu, Shun-sen Wang*, Jun Li

Institute of Turbomachinery, School of Energy and Power Engineering, Xi'an Jiaotong University, Shaanxi Engineering Laboratory of Turbomachinery and Power Equipment, No. 28 Xianning West Road, Xi'an 710049, PR China

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ABSTRACT

A novel combined supercritical carbon dioxide recompression Brayton/organic flash cycle is investigated by means of exergoeconomic analysis. The supercritical carbon dioxide recompression Brayton/organic flash cycle is a combination of a supercritical carbon dioxide recompression Brayton cycle and an organic flash cycle where the organic flash cycle absorbs waste heat from the supercritical carbon dioxide recompression Brayton cycle for power generation. Seven different organic flash cycle working fluids are examined, including *n*-Nonane, *n*-Octane, *n*-Heptane, *n*-Hexane, *n*-Pentane, R365mfc and R245fa. Parametric study is employed to investigate the effects of the some decision variables on the first and second law efficiencies and the total product unit cost of the supercritical carbon dioxide recompression Brayton/organic flash cycle and the supercritical carbon dioxide recompression Brayton cycle. The performances of the supercritical carbon dioxide recompression Brayton/organic flash cycle and the supercritical carbon dioxide recompression Brayton cycle are optimized and then compared from the perspective of thermodynamics and exergoeconomics. The results show that the second law efficiency and the total product unit cost of the supercritical carbon dioxide recompression Brayton/organic flash cycle are up to 6.57% higher and up to 3.75% lower than those of the supercritical carbon dioxide recompression Brayton cycle, respectively. Compared with the supercritical carbon dioxide recompression Brayton/organic Rankine cycle, the supercritical carbon dioxide recompression Brayton/organic flash cycle can obtain slightly higher second law efficiency, and comparable or slightly lower total product unit cost. It can also be concluded that the highest second law efficiency and the lowest total product unit cost for the supercritical carbon dioxide recompression Brayton/organic flash cycle are achieved when the *n*-Nonane is used as the organic flash cycle working fluid.

1. Introduction

A lot of efforts have been made to increase power generation efficiency and reduce the cost of power generation for nuclear power plants. Since the early 2000s, many countries have started to develop Generation IV nuclear power plants which have a high reactor outlet temperature to increase the nuclear power plant efficiency. The steam Rankine cycle and gas turbine systems have been applied for large scale power plants for many years. Generally, the ultra-supercritical steam cycle is adopted to further improve the plant efficiency instead of a steam Rankine cycle when the turbine inlet temperature is more than 550 °C. However, the reliability of the ultra-supercritical steam cycle nuclear power plant might be a problem due to the limitations of existing materials [1]. Consequently, an alternative power conversion system is required for both efficiency improvement and safety for the Generation IV nuclear power plants. Among various candidates, S-CO_2 (supercritical carbon dioxide) Brayton cycle is considered to be one of the most promising energy conversion systems in the Generation IV reactor outlet temperature region (500–900 °C) due to its advantages of simplicity, compactness, good stability, improved safety, and better economy [2]. When the reactor outlet temperature is 550 °C, the S-CO_2 can obtain a relatively high efficiency of 45.3%, which is comparable to the efficiency that the GT-MHR (Gas Turbine-Modular Helium Reactor) achieves at a significantly higher reactor outlet temperature of 850 °C [3].This is because the compression work for the S-CO_2 cycle can be significantly decreased by utilizing the sharp changes in the CO_2 thermophysical properties, resulting in a significant improvement in the efficiency. Meanwhile, Angelino [4] investigated various layouts of the

* Corresponding author.
E-mail address: sswang@xjtu.edu.cn (S.-s. Wang).

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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)
f	exergoeconomic factor (%)
h	specific enthalpy ($kJ \cdot kg^{-1}$)
i_r	interest rate
LMTD	logarithmic mean temperature difference (°C)
$\dot{m}$	mass flow rate ($kg \cdot s^{-1}$)
n	number of operation year
NK	number of system components
NP	number of system products
P	pressure (MPa)
PRc	compressor pressure ratio
$\dot{Q}$	heat transfer rate (kW)
r	relative cost difference (%)
s	entropy ($kJ \cdot kg^{-1} \cdot K^{-1}$)
T	temperature (°C, also K)
T_e	evaporation temperature of the ORC (°C)
U	overall heat transfer coefficient ($W \cdot m^{-2} \cdot K^{-1}$)
$\dot{W}$	power (kW)
x	recompressed mass flow ratio
q	quality
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, etc.	state points
ch	chemical exergy
CI	capital investment
COD	cost optimal design
cold	cold end
CON	condenser
COP	coefficient of performance
CRF	capital recovery factor
D	destruction
ex	exergy
F	fuel
FS	flash separator
HE	heater
HTR	high temperature recuperator
in	inlet; input
L	loss
LTR	low temperature recuperator
MC	main compressor
net	net
OM	operation and maintenance
out	outlet
P	product; pump
pc	pre-cooler
ph	physical exergy
pp	pinch point
R	reactor
RC	recompression compressor
ST	supercritical CO_2 turbine
sup	superheat
t	terminal
T	turbine
th	thermal
tot	total
V	valve
vap	vapor

S-CO_2 cycles, and the results showed that the supercritical CO_2 recompression cycle is the most efficient cycle among all the cycle layouts. However, a considerable amount of low-grade thermal energy (~50% of the input energy of the S-CO_2 cycle) is rejected to the cooling water in the pre-cooler when the CO_2 is cooled to some temperature (usually ~32 °C) around its critical temperature (30.98 °C) before the compression process [5,6]. Therefore, the performance of the S-CO_2 cycle can be improved by using an appropriate bottoming cycle to utilize the low-grade thermal energy in the pre-cooler.

Recently, much work has been performed on the utilization of the waste heat from the SCRBC (supercritical CO_2 recompression Brayton cycle) by using the ORCs (organic Rankine cycles). Wang and Dai [7] studied the combined SCRB/ORC (supercritical CO_2 recompression Brayton/organic Rankine cycle) system, and they concluded that 62.64% of the second law efficiency could be achieved by the SCRB/ORC with the Isobutane. Besarati and Yogi Goswami [8] compared three different SCB/ORC (supercritical CO_2 Brayton/organic Rankine cycle) cycles via thermodynamic analysis. They found that the maximum combined cycle efficiency was obtained by the SCRB/ORC cycle. Akbari and Mahmoudi [2] studied the combined SCRB/ORC cycle thermodynamically and exergoeconomically. They reported that the second law efficiency and the total product unit cost of SCRB/ORC were up to 11.7% higher and up to 5.7% lower than those of the SCRBC, respectively. Zhang et al. [9] conducted a thermodynamic analysis on a SCRBC coupled with the ORC using the LNG (liquefied natural gas) as the cold resource. Their results showed that the overall first law efficiency of the SCRB/ORC reached up to 52.12%. Nami et al. [10] and Hou et al. [11] investigated the performances of recompression and simple S-CO_2 Brayton cycles coupled with an ORC respectively for recovering the gas turbine exhaust waste heat. Their results reported that the simple S-CO_2 cycle combined with the ORC could utilize the waste heat from the gas turbine deeply. From above literature review, ORC is suitable for recovering low-grade waste heat in the SCRBC pre-cooler because of its simple structure, low working pressure and low cost. However, a major challenge for ORC is the constant temperature evaporation process, also known as the pinch problem. For the SCRB/ORC, the pinch limitation brings about a significant temperature mismatch between the CO_2 and the organic fluid during the heat transfer process, which leads to high exergy destruction in the heater.

Many studies have also been devoted to the waste heat recovery from the SCRBC using a CDTPC (CO_2 transcritical power cycle). Yari and Sirousazar [12] studied the thermodynamic performance of a combined SCRB/CDTPC (supercritical CO_2 recompression Brayton/CO_2 transcritical power cycle) for nuclear power plants. Their results showed that the first and second law efficiencies of the SCRB/CDTPC were about 5.5–26% higher than that of the single SCRBC. Wang et al.