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Performance optimization of combined supercritical CO_2 recompression cycle and regenerative organic Rankine cycle using zeotropic mixture fluid

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ABSTRACT

Thermodynamic and exergoeconomic analysis are performed for a novel combined supercritical CO_2 (S-CO_2) recompression cycle and regenerative organic Rankine cycle (ORC) using zeotropic mixture. Comprehensive parametric studies are carried out to investigate the effect of significant system parameters as pressure ratio, split ratio, evaporation temperature, pinch point temperature difference in the evaporator and the mass fraction of zeotropic mixture on the exergy efficiency and total product unit cost. Employing the multi-objective optimization method based on genetic algorithm and the TOPSIS (Technique for Order Preference by Similarity to Ideal Situation) decision making, the Pareto front solutions and optimum system parameters are obtained. In particular, several zeotropic mixtures are parameterized and used as a decision variable to participate in the multi-objective optimization process to obtain the optimal zeotropic mixture. The result shows that the optimal zeotropic mixture is R236fa/R227ea (0.46/0.54). The optimum values of exergy efficiency and total product unit cost are found to be 73.65% and 10.93 $/GJ, respectively. Furthermore, comparison analysis reveals the superiority of the proposed combined cycle to the single S-CO_2 cycle and the combined S-CO_2 cycle and basic ORC.

1. Introduction

With the depletion of traditional fossil fuels and the worsening of environmental problems, the energy issue has been becoming a serious challenge to all countries in the world increasingly. The process of international industrialization is still accelerating, and the global energy consumption will continue to grow in the future. In recent years, nuclear power has been developed rapidly to deal with the energy and environmental problems [1]. The supercritical carbon dioxide (S-CO_2) cycle has been proven to be a promising way for nuclear power generation because of its high efficiency, simplicity, compactness, better safety and economy priority [2,3]. The reason for its high efficiency is that the sudden changes in physical properties near the critical point result in low compression work, which accounts for only 30% of the expansion work [4]. The high operating pressure makes the density of the working fluid high, which in turn leads to small component size and a very compact cycle. The power density (MWe/m^3) of S-CO_2 cycle is about 46% higher than that of the conventional helium cooled reactor [4]. The S-CO_2 cycle is suitable for nuclear reactors with core outlet temperature over 500 °C and has the potential to lower capital cost when compared to steam Rankine cycle or helium Brayton cycle [5].

Angelino [6] compared different cycle configurations including the S-CO_2 recompression cycle, the S-CO_2 recompression with pre-compression cycle, the S-CO_2 recompression with reheat cycle and the pure pre-compression cycle, and found that the S-CO_2 recompression cycle is the most efficient cycle. Sarkar [7] performed exergetic analyses and optimization of S-CO_2 recompression cycle and reported that the effect of minimum operating temperature on cycle efficiency is more important than the maximum operating temperature. He also stated that more attention should be paid on heat exchangers than the turbo-machineries from the viewpoint of irreversibility. Performance and cost analyses of S-CO_2 recompression cycle were conducted by Kouta [8] who showed that the recompression cycle achieves better economics benefit than the regeneration cycle. The parameter optimization of S-CO_2 recompression cycle was performed by adopting genetic algorithm to obtain the highest exergy efficiency [9]. Furthermore, the performance parameters of S-CO_2 recompression cycle, including exergy efficiency, output power, levelized energy cost and heat exchanger area per unit power output, had been optimized by the multi-objective optimization method based on genetic algorithm [10].

In order to recover the heat discharged to the environment to further improve efficiency of the S-CO_2 cycle, researchers proposed a combination of S-CO_2 cycle and organic Rankine cycle (ORC), which obtained satisfied results. ORC has been proven to be one of the most

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Nomenclature

Glossary

A	heat transfer area, m^2
C1	compressor 1
C2	compressor 2
$c_{p,tot}$	total product unit cost, $/GJ
e	specific exergy, kJ/kg
$\dot{E}$	exergy rate, kW
f	exergoeconomic factor
h	specific enthalpy, kJ/kg
HTR	high temperature recuperator
LTR	low temperature recuperator
$\dot{m}$	mass flow rate, kg/s
P	pressure, bar
PRc	compressor pressure ratio
Q	heat capacity, kW
RE	regenerator
s	specific entropy, kJ/kg K
T	temperature, °C
T1	turbine 1
T2	turbine 2
W	output power, kW
x	split ratio
Z	capital cost, $
$\dot{Z}$	capital cost rate, $/s

Subscripts

0	ambient (temperature)
1, 2···	state points
ch	chemical exergy
D	destruction
o	outlet
E	evaporator
F	fuel
H	heat exchanger
i	inlet
in	input
k	k-th component
net	net power
P	product
ph	physical exergy
q	heat
R	reactor
RE	regenerator
t	turbine

Greek symbols

η	exergy efficiency
ηi	isentropic efficiency
ΔT	pinch point temperature difference
φ	correction factor

effective solutions for waste heat recovery because of its reliability, simplicity, high efficiency, and flexibility [11,12]. Exergoeconomic analysis of the combined S-CO_2 recompression cycle and ORC was performed by Akbari who concluded that the exergy efficiency of the combined cycle is higher than that of the S-CO_2 recompression cycle by up to 11.7% and the total product unit cost of the combined cycle is lower than that of the S-CO_2 recompression cycle by up to 5.7% [2]. Besarati et al. [13] compared S-CO_2 simple cycle/ORC, S-CO_2 recompression cycle/ORC, and S-CO_2 partial cooling cycle/ORC and found that S-CO_2 recompression cycle/ORC achieves the highest efficiency among the three configurations. Song et al. [14] employed R245fa as working fluid for the bottoming ORC and concluded that increasing evaporation temperature would significantly improve thermal performance of the combined cycle. They also reported that the combined cycle efficiency reaches to 19.1% when the split temperature and the split ratio are 340 K and 0.47, respectively. Wang [15] compared six different organic working fluids used in the combined recompression S-CO_2 cycle/ORC and showed that the isobutane has the lowest total product unit cost (9.60 $/GJ) among all the considered working fluids.

In the existing literature on the combined S-CO_2 cycle/ORC, the ORC employs basic cycle configuration without regenerator. However,

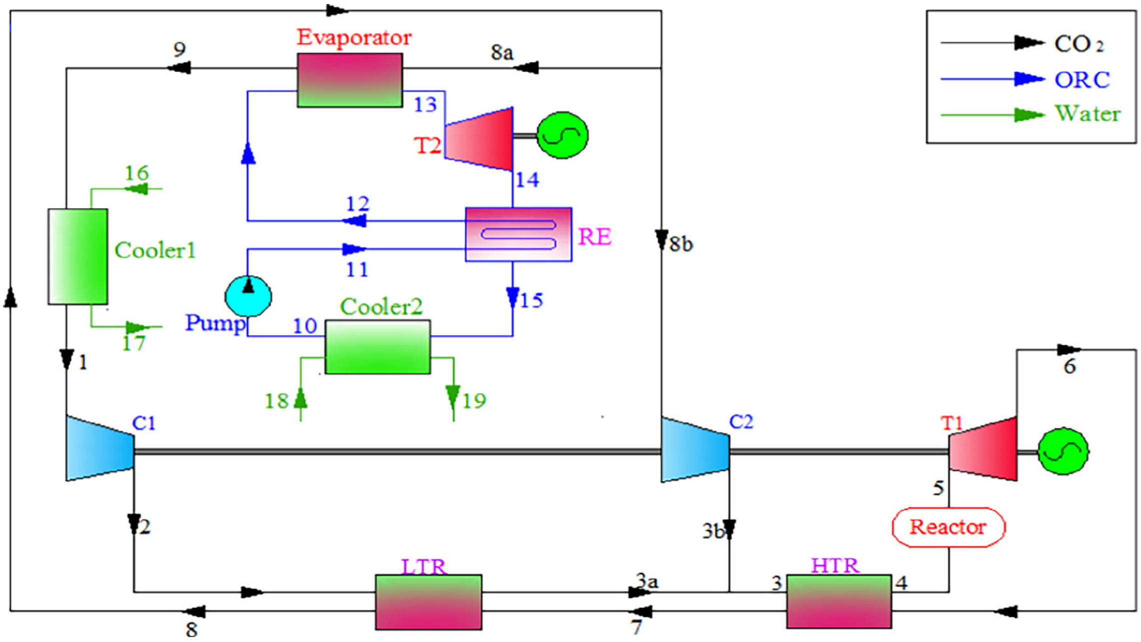

Fig. 1. Schematic diagram of the proposed system.