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Preliminary conceptual exploration about performance improvement on supercritical CO_2 power system via integrating with different absorption power generation systems

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ABSTRACT

Supercritical CO_2 (sCO_2) power system has been investigated by many scholars due to its attractive advantages of higher efficiency, compact system structure and eco-friendly working fluid. In this paper, some preliminary conceptual exploration about performance improvement on sCO_2 power system by integrating with two types of absorption power generation (APG) systems are conducted. Parameter analysis, genetic algorithm (GA) optimization and exergy analysis are carried out quantitatively for the proposed combined sCO_2/APG systems based on the self-built simulation platform from the viewpoints of thermodynamics and economics. Parameter analysis results reveal that there exist optimal compressor pressure ratio to maximize the thermal efficiency or minimize the total product unit cost. Higher turbine inlet temperature and lower absorber temperature could contribute to the overall system performance. In addition, compared with the stand-alone sCO_2 system, improvements of 5.98% and 5.07% in thermodynamics as well as promotion of 4.24% and 2.19% in economics can be obtained for sCO_2/LiBr-H_2O system and sCO_2/ammonia water system, respectively. Furthermore, exergy analyses show that the main exergy destructions occur in the reactor and the cooler and the proposed combined sCO_2/APG system could effectively reduce around half of the exergy destruction within the cooler of the stand-alone sCO_2 system.

1. Introduction

Nowadays, energy situation and environmental pollution problems become increasingly severe, especially in developing countries. Exploring renewable energy and developing high-efficiency energy conversion system are effective methods to relieve current situation. The sCO_2 power system, as a type of promising energy converter, attracts a great deal of attention due to the advantages of high efficiency, compact construction. Besides, the CO_2 working fluid is eco-friendly, safe and non-toxic [1–3].

Various heat sources including nuclear energy [4], solar energy [5], geothermal energy [6] and other industries [7] can be exploited by the sCO_2 power system. Nuclear energy, as a kind of environmentally friendly, economical and reliable energy, has been considered as the potential alternative to currently widely used fossil fuels. The sCO_2 power system is much more appropriately applied to the conventional pressurized water reactors [8] and nuclear fusion reactors [9]. Dostal [10] found that the recompression layout was the best configuration for the next generation nuclear reactor application.

The main work about the recompression sCO_2 power system mainly focuses on the basic theoretical analysis and key devices investigation, including system thermodynamic analysis [11], economic analysis [12], off-design analysis [13], dynamic behaviors analysis [14], turbomachinery design [15], and heat transfer enhancement [16] up to now. Jahar [11] performed an exergetic analysis and optimization for the recompression sCO_2 power system. He found that the system second law efficiency was much more sensitive to isentropic efficiency of the turbine than that of the compressor. Floyd et al. [13] studied the system off-design behaviors for the seasonal variation in the heat sink diversification on the basis of the preliminary design of the main

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Nomenclature

A	area, m^2
C	solution concentration
$\dot{C}$	cost rate, $\$\cdot h^{-1}$
CRF	capital recovery factor
c	cost per exergy unit, $\$\cdot GJ^{-1}$
cp,total	total product unit cost, $\$\cdot GJ^{-1}$
eff	efficiency, %
E	exergy, kJ
$\dot{E}$	exergy rate, $kJ\cdot h^{-1}$
e	specific exergy, $kJ\cdot kg^{-1}$
h	specific enthalpy, $kJ\cdot kg^{-1}$
I	exergy destruction, kJ
i	interest rate, %
M	molar mass
m	mass flow rate, $kg\cdot s^{-1}$
n	system service length, year
p	pressure, kPa
PR	compressor pressure ratio
Q	heat rate, kW
s	entropy, $kJ\cdot kg^{-1}\cdot K^{-1}$
T	temperature, °C
W	power, kW
x	mass separation ratio
Z	capital cost of component, $
$\dot{Z}$	capital cost rate, $\$\cdot h^{-1}$

Greek symbols

η	efficiency, %
γ	weighting coefficient
τ	annual plant operation hours
ε	effectiveness
ΔT	temperature difference, K

Subscripts

0	dead (environmental) state
1,2… 14; 01,02… 012	state points
CO_2	working fluid
ch	chemical
components	system components
core	reactor core
cw	cooling water
ex	exergy efficiency
in	flow into
k	serial number of system component
net	net power
out	outlet
ph	physical
pump	working fluid pump
ref	reference value
s	isentropic process
th	thermal
total	sum

Abbreviations

Abs	absorber
AMW	ammonia water
APG	absorption power generation
AST	absorption turbine
GA	genetic algorithm
Gen	generator
HTR	high temperature recuperator
LTR	low temperature recuperator
LiBr	lithium bromide
MC	main compressor
ORC	organic Rankine cycle
PCHE	print circuit heat exchanger
RC	recompression compressor
SHX	solution heat exchanger
ST	sCO_2 turbine
sCO_2	supercritical CO_2
tCO_2	transcritical CO_2

components. They revealed that a degree-of-freedom of the compressor performance was needed to gain high efficiency and constant thermal power under the elevated heat sink temperature conditions. Minh et al. [17] made an investigation on the advanced control strategies of the recompression sCO_2 power system driven by solar energy and presented its dynamic behaviors. They found that compared with the traditional process, a significant improvement up to 37.1% in total energy output can be provided by means of the inventory control scheme.

Furthermore, it has already been a well-accepted fact from the literature that the overall performance of the recompression sCO_2 power system can be enhanced via integrating with different low-grade waste heat recovery systems to make the utmost of the heat of cooling. Many scholars have done amounts of work on this. Akbari et al. [18] proposed the combined sCO_2/ORC (organic Rankine cycle) system and performed a detailed thermodynamic and exergoeconomic analysis. They observed that the most cost-saving operation condition could be got when RC318 refrigerant was used. Wang et al. [19,20] suggested a combination of sCO_2 system and tCO_2 system to strengthen the performance of stand-alone recompression sCO_2 power system. Their optimization results pointed out that the combined sCO_2/tCO_2 system had a comparable exergetic efficiency with the sCO_2/ORC system. Li et al. [21] integrated the recompression sCO_2 power system with a low-temperature regenerative Kalina system. Their results showed that the second law efficiency and total product unit cost of the proposed combined sCO_2/Kalina system were able to gain 5.50% and 8.02% improvement, respectively.

Apart from the above investigation, some scholars devoted to investigate the combination of recompression sCO_2 power system with absorption systems. As is well-known, absorption system mainly using the LiBr-H_2O solution or ammonia water as working fluids can be driven by low-grade heat to produce refrigeration or more low-temperature heat. The mixture working fluids can provide a better thermodynamic match in temperature with the heat source and heat sink [22]. Wu et al. [23] connected the absorption refrigeration system with the recompression sCO_2 power system to produce power and cooling together. They found that the combined system could produce 71.76 MW cooling at the expense of 0.36 MW electric power under the basic design conditions. Li et al. [24] made a comparative study utilizing LiBr-H_2O solution and ammonia water as working fluids to recover the heat of cooling from the recompression sCO_2 power system. They revealed that the combined sCO_2/LiBr-H_2O system had a greater potential in terms of generating cooling and power. Recent years, a novel conception, called absorption power generation system, was proposed to recover the low-grade heat based on the characteristics of mixture [25]. Shokati et al. [26] made a comparative analysis between Rankine cycle system and APG cycle system. They argued that LiBr-H_2O system with the lowest exergy destruction cost rate had the highest thermal efficiency.