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Exergy and exergoeconomic analyses of a supercritical CO_2 cycle for a cogeneration application

Xurong Wang, Yi Yang, Ya Zheng, Yiping Dai*

School of Energy and Power Engineering, Xi'an Jiaotong University, Xi'an, China

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Detailed exergy and exergoeconomic analyses are performed for a combined cogeneration cycle in which the waste heat from a recompression supercritical CO_2 Brayton cycle (sCO_2) is recovered by a transcritical CO_2 cycle (tCO_2) for generating electricity. Thermodynamic and exergoeconomic models are developed on the basis of mass and energy conservations, exergy balance and exergy cost equations. Parametric investigations are then conducted to evaluate the influence of key decision variables on the sCO_2/tCO_2 performance. Finally, the combined cycle is optimized from the viewpoint of exergoeconomics. It is found that, combining the sCO_2 with a tCO_2 cycle not only enhances the energy and exergy efficiencies of the sCO_2, but also improves the cycle exergoeconomic performance. The results show that the most exergy destruction rate takes place in the reactor, and the components of the tCO_2 bottoming cycle have less exergy destruction. When the optimization is conducted based on the exergoeconomics, the overall exergoeconomic factor, the total cost rate and the exergy destruction cost rate are 53.52%, 11243.15 \$/h and 5225.17 \$/h, respectively. The optimization study reveals that an increase in reactor outlet temperature leads to a decrease in total cost rate and total exergy destruction cost rate of the system.

1. Introduction

Many efforts have been devoted to the high efficiency and the cost reduction of electricity generated by nuclear power plant toward the successful future utilization of nuclear power. These advanced energy conversion technologies include the gas turbine-modular helium reactor (GT-MHR) [1–4] and the supercritical CO_2 Brayton cycles (sCO_2) [5–7]. Comparison to the GT-MHR, the main advantage of the sCO_2 cycle is the comparable efficiency at considerable lower reactor outlet temperature. With a reactor outlet temperature of 550 °C, the efficiency of sCO_2 cycle can reach 45.3%, which is comparable with the helium Brayton cycle at a significantly higher temperature (850 °C) [6]. This is because by utilizing the abrupt property changes near the critical point of CO_2 the compressor work can be reduced, resulting in the significant efficiency improvement. Cooling the CO_2 (to about 32 °C) before compression process is beneficial. This leads to a considerable thermal energy (at a rate of about 300 MW) rejected to the heat sink in the pre-cooler [8,9]. The performance of the sCO_2 cycle can be improved after utilization of that thermal energy in low-grade waste heat recovery systems.

Some investigations have been carried out on the recovery of waste heat from sCO_2 cycles. Chacartegui et al. [10,11] studied the utilization of this waste heat for power production using Organic Rankine Cycles (ORCs). The results showed that the thermal efficiency of the sCO_2 was improved by 7–12%, which depends on the turbine inlet temperature [11]. It should be noted that the simple sCO_2 configuration is considered in that study. Sánchez et al. [12] investigated the utilization of sCO_2 waste heat to drive ORCs using mixtures of hydrocarbons in the bottoming cycle, which was also on the basis of the simple sCO_2 configuration. They observed that the performance of the combined cycle was directly affected by the mixture's composition. Besarati and Goswami [13] considered a thermodynamic comparison of three different sCO_2/ORC combined cycles. They reported that the largest efficiency increase was achieved by using a simple sCO_2 configuration as the topping cycle. The maximum overall efficiency, however, was obtained by the recompression sCO_2/ORC cycle. Zhang et al. [14] studied a sCO_2 part-flow cycle combined with an ORC with liquefied natural gas as the heat sink. They showed that the combined cycle achieved 52.12% of overall thermal efficiency. In another study, Akbari and

* Corresponding author. School of Energy and Power Engineering, Xi'an Jiaotong University, 28 Xianning West Road, Xi'an, Shaanxi, 710049, China.

E-mail addresses: wang.xu.rong.1@stu.xjtu.edu.cn (X. Wang), ypdai@mail.xjtu.edu.cn (Y. Dai).

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Nomenclature

A	heat transfer area, m^2
$\dot{C}$	cost rate, $/h
c	cost per exergy unit, $/GJ
$\dot{E}$	exergy rate, W
f	exergoeconomic factor
h	specific enthalpy, Jkg^{-1}
$\dot{m}$	mass flow rate, kgs^{-1}
P	pressure, bar
PRc	compressor pressure ratio
$\dot{Q}$	heat addition, W
r	relative cost difference
s	specific entropy, Jkg^{-1}K^{-1}
T	temperature, °C, also K
$\dot{W}$	work flow rate-power, W
x	recompressed flow ratio
YD	exergy destruction ratio, %
$\dot{Z}$	capital cost rate, $/h

Greek symbols

η	efficiency
ε	effectiveness

Subscripts

0	environmental state
c	cooling water
cnd	condenser
D	destruction
ex	exergy
HTR	high temperature recuperator
in	inlet
k	kth component
LTR	low temperature recuperator
MC	main compressor
p	pump
pc	pre-cooler
R	reactor
RC	recompression compressor
th	thermal
total	total

Mahmoudi [15] investigated a combined recompression sCO_2/ORC cycle from the viewpoints of exergy and exergoeconomics. They found that the exergy efficiency of sCO_2 cycle was enhanced by up to 11.7% and the total product unit cost was reduced by up to 5.7%. The results also indicated that the highest exergy efficiency and the lowest product unit cost for the sCO_2/ORC cycle were obtained when isobutane and RC318 were used as the ORC working fluid, respectively. The ORC has low operating pressure and low cost because of simplicity. After finding appropriate working fluids, ORC can be well suited to any type of heat sources. However, an important limitation is the constant temperature evaporation which is the so called pinch problem. This leads to a significant mismatch of the two fluid states and generates a lot of irreversibility in the sCO_2/ORC cogeneration system.

Compared to the ORC, the transcritical CO_2 cycle (tCO_2) shows a better match. The evaporation temperature profile of the CO_2 is gliding, generating a closer fit of the two curves, thereby having no pinch limitation. A comparison between the ORC and the tCO_2 cycle shows that a power system with CO_2 as the working fluid has a higher power output and is more compact than the one with organic fluids as the working media [16].

Recently, Yari and Sirousazar [17] proposed and analyzed the utilization of waste heat from the sCO_2 cycle for electricity generation using a tCO_2 cycle. They paid more attention to the combined cycle irreversibility. They showed that the second law efficiency of the recompression sCO_2/tCO_2 cycle was 5.5–26% higher than that of the single sCO_2 cycle. Further, the exergy destruction of the new combined cycle was 6.7–28.8% lower than that of the stand-alone sCO_2 cycle. Later, Wang et al. [18] investigated a combined recompression sCO_2/tCO_2 cycle from the viewpoint of thermodynamics and economics. The results showed that the capital cost per net power output of the combined cycle was 6.6 k$/kW, which was about 6% more expensive than that of the single sCO_2 cycle. They reported the effects of key decision variables on the combined cycle performance, however, without a further parametric optimization. The cost of the reactor is also not considered in their study. In another work they conducted a thermodynamic comparison and optimization of two different configurations of sCO_2/tCO_2 cycle [19]. They showed that the thermal efficiencies of recompression and simple configurations of the sCO_2 cycle were improved by 10.12% and 19.34%, respectively. Further, the simple and recompression sCO_2/tCO_2 cycles had a power ratio of 16.21% and 11.26%, respectively.

The above mentioned background reveals that much research has been devoted to sCO_2/ORC cycles concerning thermodynamics, performance comparison, exergy and exergoeconomic analyses, while little research has been done on the combination of sCO_2 cycles and a tCO_2 cycle. Besides, the available literature merely concerns a thermodynamic assessment of sCO_2/tCO_2 cycles. A comprehensive exergy and exergoeconomic study on this cogeneration system, to our knowledge, has not yet been performed. Making a right decision from the economic perspective needs a detailed exergoeconomic investigation as well as the thermoeconomic analysis.

This paper focuses on the energy, exergy and exergoeconomic analyses of the sCO_2/tCO_2 cycle. Firstly, the combined cycle is analyzed from the viewpoints of energy and exergy. The theory of exergetic cost is then applied to the combined cogeneration cycle. Further, a parametric study is performed to reveal the effects of decision variables on the energy efficiency, exergy efficiency and total cost rate of the system. Finally, the sCO_2/tCO_2 cycle is optimized from the viewpoint of exergoeconomics using a genetic algorithm and the obtained results are compared. It is expected that the findings of present work may help to find an efficient and economical sCO_2 cycle for nuclear power plants.

2. System description and assumptions

Fig. 1 illustrates the configuration of combined sCO_2/tCO_2 cycle. The cogeneration system actually comprises a recompression sCO_2 topping cycle and a simple tCO_2 bottoming cycle. The CO_2 from the pre-cooler 2 enters the main compressor where it is compressed to a pressure of around 200 bar. The stream is first preheated in the LTR (low temperature recuperator) and then merged with the stream exiting the recompression compressor (point 3). The mixture is heated in the HTR (high temperature recuperator), evaporates in the reactor and undergoes an expansion process in the turbine 1. After expansion, the CO_2 flows across the HTR and then the LTR. The CO_2 at LTR exit (point 8) is divided into two streams: stream 8a and stream 8b. The stream 8a enters the pre-