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Performance analysis and parametric optimization of supercritical carbon dioxide (S-CO_2) cycle with bottoming Organic Rankine Cycle (ORC)

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A B S T R A C T

Supercritical carbon dioxide (S-CO_2) cycle is proven to be one promising alternative to provide high efficiency and has been developed for a wide range of energy conversion applications. Thermal efficiency of the S-CO_2 cycle can be further improved by incorporating an appropriate bottoming cycle utilizing the residual heat. In this paper, an Organic Rankine Cycle (ORC) is added to the S-CO_2 cycle for heat recovery. Different recuperative ratios of the topping S-CO_2 cycle are considered and the influence of heat source initial temperature and total heat load on the bottoming ORC is evaluated. Two configurations of the S-CO_2-ORC combined cycle system are presented, one without a pre-cooler and the other still with a pre-cooler, corresponding to total and partial residual heat recovery respectively. Though the entire residual heat recovery by the bottoming cycle could definitely increase the system thermal efficiency, the low ORC evaporation temperature and mediocre ORC performance leads to a limited improvement. While in the combined cycle system with a pre-cooler, higher ORC evaporation temperature could be attained and it has a remarkable effect on the ORC performance, even though part of the topping cycle residual heat is discharged to the ambient. The simulation results reveal that the S-CO_2-ORC combined cycle system performance could be significantly improved through this parametric optimization. The recompression S-CO_2 cycle with bottoming ORC is then analyzed and thermal performance is improved based on the previous optimization results. The bottoming ORC could effectively recover the residual heat of the topping S-CO_2 cycle and increase the system thermal efficiency, thus it can be considered and applied in similar practical cases.

1. Introduction

Supercritical carbon dioxide (S-CO_2) cycle has emerged as a promising way for high efficiency power generation since firstly proposed by Feher [1] and Angelino [2]. The additional advantages of S-CO_2 cycle are the use of an abundant, nontoxic and environmental friendly working fluid and a simple layout with compact turbomachinery and heat exchangers. Plenty of studies have been implemented on the field of S-CO_2 cycle in decades, including layout innovation [3–6], performance analysis [7–10], components design [11–14] and system development [15–19]. It is recognized that nuclear [20,21], fossil fuel [22–24], waste heat [25,26] and renewable energy such as solar thermal [27–30], biomass energy [29], geothermal energy [31] and fuel cell [32] are potential application areas of S-CO_2 cycle.

Pressure ratio of the S-CO_2 cycle is generally small and the turbine outlet temperature is relatively high. This large amount of heat load should be utilized to increase cycle efficiency. Recuperator is typically installed in S-CO_2 cycle systems. However, the total heat load of the hot S-CO_2 stream cannot be entirely recovered through regeneration due to the nonideal heat exchange effectiveness. In other words, a pre-cooler is needed and the ending low-grade heat is discharged to the ambient. In a different way from the recuperator, a combined cycle system can be set up by adding a bottoming cycle in the stand-alone S-CO_2 cycle to recover the residual heat load. The topping S-CO_2 cycle would provide the heat source to be

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Nomenclature

W	power, kW
$\dot{m}$	mass flow rate, kg/s
h	specific enthalpy, kJ/kg
Q	heat load, kW
T	temperature, K
P	pressure, kPa
c_p	specific heat capacity, kJ/kg·K
Greek symbols	
η	efficiency
ε	Recuperative ratio
Subscripts	
comp	compressor
recup	recuperator
T	turbine
$pre-c$	pre-cooler
$S-CO_2$	supercritical carbon dioxide cycle
in	input
net	net power output
pump	pump
cond	condenser
wf	working fluid
ORC	Organic Rankine Cycle
global	global thermal efficiency
06	recuperative outlet as well as heat recovery inlet for S-CO_2
07	heat recovery outlet for S-CO_2
Acronyms	
S-CO_2	supercritical carbon dioxide cycle
ORC	Organic Rankine Cycle
BMPC	Bechtel Marine Propulsion Corporation

absorbed by the bottoming cycle with a working fluid capable of vaporizing at a low temperature. In the category of alternative cycles, Organic Rankine Cycle (ORC) has been proven to be an effective method to utilize low-grade heat sources [33–38] and applied as the bottoming cycle in many cases [39–43]. The combined cycle system comprising a topping S-CO_2 cycle and a bottoming ORC has been presented and analyzed in some previous researches. Pérez-Pichel et al. [7] implemented a bottoming ORC on an S-CO_2 Brayton cycle configuration for a sodium reactor and the potential performance improvement was explored, comparing with other system optimizations such as cycle parameters adjustment and dual cycles with a steam Rankine cycle. Chacartegui et al. [44] presented various stand-alone closed S-CO_2 cycles and a combined cycle with an ORC for solar power plants. Preliminary results showed that these cycles were promising technologies and had the potential to compete in terms of efficiency and costs with other conventional technologies. Sánchez et al. [45] studied a combined cycle with a topping S-CO_2 cycle and a bottoming ORC using both pure substances and mixture of hydrocarbons. A 7% improvement in global efficiency with respect to the stand-alone topping S-CO_2 cycle could be obtained Besarati and Goswami [46] added an ORC to different S-CO_2 layouts for concentrating solar power applications and the simulation results showed that the combined recompression-ORC cycle achieved the highest system thermal efficiency. Zhang et al. [47] conducted thermodynamic analysis of an S-CO_2 part-flow cycle coupled with an ORC to investigate the effects of some key parameters on the system performance.

In this paper, an ORC system is added to a regenerative S-CO_2 cycle system for residual heat recovery. Different recuperative ratios of the topping S-CO_2 cycle are considered, which implies that the heat source absorbed by the bottoming ORC varies. Influence of heat source initial temperature and total heat load on the ORC performance is evaluated. The bottoming ORC could recover total or partial of the topping cycle residual heat, corresponding to S-CO_2-ORC combined cycle systems without and with a pre-cooler. Thermodynamic analysis and parametric optimization of the bottoming ORC is conducted to achieve the maximum thermal efficiency of the combined cycle system. The recompression S-CO_2 cycle with a bottoming ORC is then analyzed based on the previous optimization results, which aims at a further improvement on the system performance.

2. Cycle configuration

2.1. Regenerative S-CO_2 cycle

Fig. 1 shows the schematic diagram of a regenerative S-CO_2 cycle system, which consists of a compressor, a heat exchanger (evaporator) to absorb heat, a turbine, a recuperator and a pre-cooler. The S-CO_2 is first pressurized by the compressor and then it absorbs heat in the recuperator and from the heat source in series. Next, the high temperature and high pressure S-CO_2 enters the turbine where it expands to produce power. Then, the S-CO_2 hot stream goes through the recuperator and transfers energy to the clod stream leaving the compressor. Afterwards in the pre-cooler, the S-CO_2 continues to be cooled by the cold sink.

2.2. S-CO_2-ORC combined cycle

The S-CO_2-ORC combined cycle contains a topping S-CO_2 cycle and a bottoming ORC. The two cycles are coupled via a shared heat exchanger. The S-CO_2 from the recuperator goes through the heat recovery unit and provides the heat source for ORC. In the

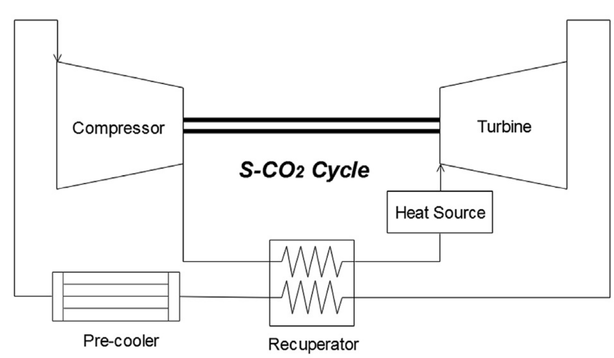

Fig. 1. Schematic diagram of a regenerative S-CO_2 cycle system. (a) S-CO_2-ORC combined cycle system without a pre-cooler. (b) S-CO_2-ORC combined cycle system with a pre-cooler.