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Exergy analysis of a 1000 MW single reheat supercritical CO_2 Brayton cycle coal-fired power plant

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ABSTRACT

This study proposes an optimization method for the supercritical carbon dioxide (S-CO_2) Brayton cycle in a 1000 MW single-reheat S-CO_2 coal-fired power plant based on the second law of thermodynamics. The effects of parameters and configurations on S-CO_2 cycle efficiencies and component irreversibility are studied. The analysis reveals that variations in parameters and configurations have more remarkable effects on the irreversibility of heat exchangers, particularly on the high-temperature recuperator (HTR) and cooler (COL), than on that of turbo machines. The results show that the optimum parameter of turbines provides a higher expansion ratio for the low-pressure turbine (LPT) than for the high-pressure turbine (HPT). The effects of split ratio to economizer (ECO) have contradicting results on cycle thermal and exergy efficiencies given that the irreversibility of HTR decreases with the increase in the split ratio to ECO. The minimum cycle pressure drastically affects the irreversible interaction between HTR and COL because of the nonlinear characteristics of CO_2 near its critical point. Double compression and the Case 2 of the ECO configuration is more reasonable for S-CO_2 power plants. The main differences between the S-CO_2 and traditional steam power plant are that exergy loss ratio of fuel combustion and exergy efficiency of the water wall, screen heaters, primary heaters are noticeably higher in the S-CO_2 boiler than those in the traditional steam boiler. The overall exergy efficiency of the innovative single-reheat 1000 MW S-CO_2 coal-fired power plant is 45.4%, which is approximately 3.5% higher than that of the traditional ultra-supercritical steam plant.

1. Introduction

Improving the efficiency of power-generating units and reducing the emission of pollutants are the eternal theme and objective of the power industry research. The Rankine steam cycle is mainly utilized as the mainstream energy conversion system in current boiler systems. The main approach to improve the efficiency of traditional power plants includes the use of high-parameter double-reheat ultra-supercritical technology and the European Union-financed AD700 project [1]. The development of traditional Rankine steam cycle power-generating units reaches the ceiling because of material and technical constraints. The supercritical carbon dioxide (S-CO_2) Brayton cycle is an alternative technology that can be used to improve the efficiency of power-generating units and to break through the traditional bottlenecks of existing power-generating technologies [2]. In the 1960s, Feher and Dekhtiarey [3,4] analyzed several supercritical cycles and concluded that the S-CO_2 Brayton cycle provided high thermal efficiency and power density while requiring simple turbomachinery. Henceforth, the S-CO_2 Brayton cycle has been considered as a viable alternative to various power generating technologies and has received widespread attention [5–7].

The S-CO_2 Brayton cycle has been widely applied to nuclear power [8,9], solar power [10–13], geothermal power [14,15], gas turbine [16,17] and so on. In 2001, Kato et al. [8] performed thermodynamics analysis to illustrate that the direct S-CO_2 cycle was more competitive than liquid metal cooling fast nuclear reactors. Dostal [9] systematically investigated some compound S-CO_2 Brayton cycles and concluded that the S-CO_2 Brayton recompression cycle exhibited excellent thermal performance for above 500 °C high-temperature range which was well suited to current mainstream heat source. Lately, Reyes-Belmonte et al. [12] performed thermodynamics optimization of the S-CO_2 recompression cycle for an innovative central receiver solar power

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Nomenclature

E	exergy (MW)
E_l	exergy loss (MW)
w	specific work (kJ/kg)
h	specific enthalpy (kJ/kg)
s	specific entropy (kJ/kg K)
m	mass flow rate (kJ/kg K)
q	specific heat transfer (kJ/kg)
e	specific exergy (kJ/kg)
T_0	previously defined reference temperature (K)
η^e	exergy efficiency (%)
η_{th}	thermal efficiency (%)
φ	exergy loss coefficient
I	fraction of irreversibility
ε	exergy loss ratio
α	turbine expansion ratio

Subscripts

in	parameters in the system
out	parameters outside the system
COLs	parameters of precooler and intercoolers
MCs	parameters of main compressors
Rs	parameters of recuperators
TURs	parameters of all turbines
sc	parameters of S-CO$_2$ cycle system
b	parameters of boiler system
tot	parameters of overall coal-fired power plant
k	the kth component (Fig. 1)
De	decomposer
Com	combustor
Sep	separator
Fs	splitter
WW	water wall
P-SH	primary superheater
S-SH	screen superheater
F-SH	final superheater
ECO	economizer
APH	air preheater (Fig. 2)
LTR	low-temperature recuperator
HTR	high-temperature recuperator
MC	main compressor
BC	bypass compressor
COL	cooler (Fig. 3)
PC	precooler
IC	intercooler
HPT	high-pressure turbine
LPT	low-pressure turbine
S-Heater	superheater
R-Heater	reheater

plant. Their results indicated that the cycle net thermal efficiency was close to 50% which was also well suitable for solar power plants. Ahn et al. [18] reviewed the S-CO$_2$ Brayton cycle technology and emphasized its high efficiency, flexibility and compactness that could be widely adapted to the application in nuclear, fossil fuel, waste heat and renewable heat sources. From the above studies, it could be seen that S-CO$_2$ Brayton recompression cycle exhibited excellent thermodynamic performance based on energy analysis and further investigations could also be constructed for S-CO$_2$ coal-fired power plants.

In 2013, Le et al. [19] proposed the conceptual design and economic evaluation of a S-CO$_2$ coal-fired power plant. The results indicated that introducing S-CO$_2$ Brayton cycle to coal-fired power generation plants was an essential technology to improve plant thermal efficiency. Lately, Mecheri and Le Moullec [20] performed the sensitivity analysis of key parameters such as heat exchanger pinches, component pressure losses, boiler and cycle configurations on the thermodynamic performance of the S-CO$_2$ coal-fired power plant. They also concluded that the optimized S-CO$_2$ coal-fired power plant could exhibit a 47.8% overall plant net efficiency with achievable current coal-fired conditions (30 MPa/620 °C). Xu et al. [21] went further to analyze that introducing intercooling and/or reheating into coal-fired power plant apparently elevated thermal efficiencies. Yang et al. [22] investigated a preliminary numerical simulation of the coupled heat transfer between combustion and fluid heating of a 300 MW supercritical CO$_2$ boiler. Their results indicated the feasibility of S-CO$_2$ coal-fired power plant and it was necessary to further analyze the exergy loss distribution of the whole S-CO$_2$ coal-fired power plants based on the second law of thermodynamics. The above studies analyzed the effect of some cycle configurations and parameters for S-CO$_2$ coal-fired power plants, and constructed the S-CO$_2$ coal-fired power plants optimization method based on the optimal thermal efficiency using the energy analysis. However, some key parameters which involved S-CO$_2$ boiler heating surface arrangement, and some cycle configurations (compression and economizer configuration) lacked the further investigations for S-CO$_2$ coal-fired power plants. Moreover, comprehensive energy and exergy analysis based on the second law of thermodynamics was necessary to optimize the performance of S-CO$_2$ coal-fired power plants.

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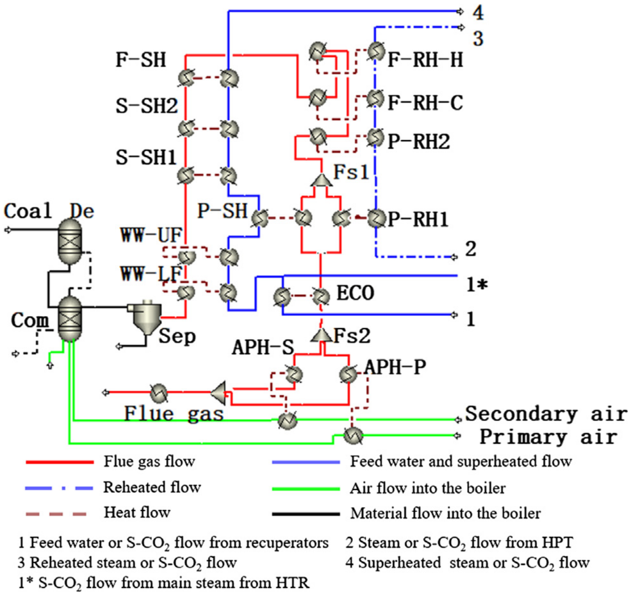

Fig. 1. Schematic of a single-reheat boiler for coal-fired power plants.

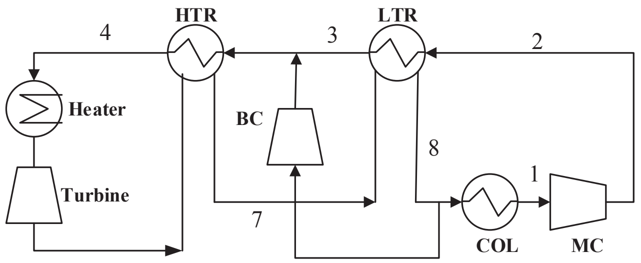

Fig. 2. Simplified schematic of S-CO$_2$ Brayton recompression cycle.