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Connected-top-bottom-cycle to cascade utilize flue gas heat for supercritical carbon dioxide coal fired power plant

Enhui Sun[a], Jinliang Xu[a,*], Mingjia Li[b], Guanglin Liu[a], Bingguo Zhu[a]

[a] Beijing Key Laboratory of Multiphase Flow and Heat Transfer for Low Grade Energy Utilization, North China Electric Power University, Beijing 102206, China
[b] Key Laboratory of Thermo-Fluid Science and Engineering of Ministry of Education, School of Energy & Power Engineering, Xi'an Jiaotong University, Xi'an, Shaanxi 710049, China

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ABSTRACT

For coal fired power plant, the supercritical carbon dioxide Brayton cycle (S-CO_2) is difficult to absorb flue gas heat in a wide temperature range of 120–1500 °C. Here, novel methods are developed to cascade utilize flue gas heat, in which energies in high, moderate and low temperature levels are extracted by top cycle, bottom cycle or flue gas cooler (FGC), and air preheater, respectively. The cascade utilization shall satisfy the criterion that *CO_2 temperature entering boiler for top cycle equals to CO_2 temperature leaving boiler for bottom cycle*. The separate-top-bottom-cycle (STB) is proposed, in which no any component is shared by top and bottom cycles. Six possible bottom cycles are studied. The thermodynamics analysis is coupled with heat transfer and pressure drop analysis for whole power plant. It is found that the main vapor pressure of bottom cycle can be the "best" parameter to be adjusted over a wide range of 15–35 MPa to couple and optimize top and bottom cycles. Then, the *parameter coordination principle* is proposed to share specific components for top and bottom cycles. Thus, the separate cycles are converted into a connected cycle to simplify the whole system layout. The connected cycle has a power generation efficiency of 51.82% at main vapor parameters of 700 °C/35 MPa, significantly higher than available supercritical water-steam Rankine cycle power plant. The findings in this paper give a clue to further raise the power generation efficiency for large scale S-CO_2 coal fired power plant.

1. Introduction

High pressure water-steam Rankine cycle has been used for large scale power generation for more than one century, since the first coal fired power plant was put into operation in 1882 [1]. At the moment, the power generation efficiency is about 47% for large scale (~1000 MW) supercritical water-steam Rankine cycle power plant [2]. The classical thermodynamics tells us that the system efficiency can be further increased by increasing vapor temperature entering turbine. However, such improvement is restricted by temperature tolerance limit of materials. For example, the chemical reaction between water-steam and solid materials is enhanced at ultra-high temperature such as 700 °C, introducing the difficulty to further explore efficiency potential [3].

Scientists and engineers are searching new technologies for compact power systems. It is known that renewable energy such as wind energy or solar energy are unstable. When these energies are connected with a power grid, the power grid becomes fragile [4]. An effective way to create robust power grid is to develop hybrid power systems including renewable energy and coal fired power plant [5]. The coal fired power plant should have the capability to adjust power load at a fast speed. The coal fired power plant should be designed in a compact way to have small thermal inertia. Fundamentally, a water-steam Rankine cycle system is difficult to satisfy this requirement, because some components such as condenser operate in a vacuum pressure such as ~6 kPa [6] to cause low fluid density and large component size. Distributed energy utilization also demands smart and compact power systems [7,8].

Supercritical carbon dioxide Brayton cycle (called S-CO_2 cycle here) offers benefits to breakthrough above limitations. First, the thermal efficiency of a S-CO_2 cycle can be higher than a supercritical water-steam Rankine cycle [9]. Second, CO_2 is an inertia fluid to yield the weak chemical reaction between high temperature CO_2 and solid material [10], making it possible to further raise vapor temperature entering turbine. Third, S-CO_2 is a Brayton cycle to operate the whole system in high pressures such as > 7.38 MPa, resulting in high fluid densities to significantly reduce component sizes of turbines and coolers [11,12].

Sulzer [13] was the first to propose S-CO_2 cycle, which was

* Corresponding author.
E-mail address: xjl@ncepu.edu.cn (J. Xu).

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Nomenclature

C	compressor
CTB	connected-top-bottom-cycle
d	inside tube diameter, mm
DRH	double reheating
f	frictional coefficient
FGC	flue gas cooler
g	gravity acceleration
G	mass flux in a single tube, $kg/m^2 s$
h	specific enthalpy, kJ/kg
HTR	high temperature recuperator
l	tube length, m
LTR	low temperature recuperator
m	mass flow rate, kg/s
n	the number of tubes
N	number of flow length segments
P	pressure, MPa
PACC	partial cooling cycle
PRCC	pre-compression cycle
PH	preheater
Q	heat transfer rate, MW
RC	recompression cycle
Re	Reynolds number
RH	reheating
S-CO_2	supercritical carbon dioxide
SEC	split expansion cycle
SH	superheater
SHC	split heating cycle
SRC	simple recuperated cycle
STB	separate-top-bottom-cycle
T	turbine
T	temperature, °C
TTH	thermodynamic-thermal-hydraulic
u	flow velocity, m/s
x_{abs}	CO_2 flow rate split ratio
α_{ex}	excess air ratio

Subscripts

1, 2, 3…	state points of top cycle
1b, 2b, 3b…	state points of bottom cycle
abs	absorb
AP	air preheater
b	boiler
c	critical
e	electric
ex	exhaust
f	friction
fg	flue gas
i	in
LHV	lower heating value
o	out
p	pinch
s	isentropic
sec	secondary

Greek symbols

ρ	density, kg/m^3
ΔP	pressure drop
η_{th}	thermal efficiency
η_b	boiler efficiency
η_e	power generation efficiency
$\eta_{th,b}$	bottom cycle thermal efficiency
θ	inclination angle

analyzed by Feher [14]. The “Feher cycle” has been called in literature. Great attention has been paid on S-CO_2 cycle in recent years. Most of studies have been focused on S-CO_2 cycles driven by nuclear energy [15–17], solar energy [18–20], or waste heat from gas turbine [21–23], including thermodynamics analysis [18,24,25], heat transfer characteristics [26–28] and small-scale component demonstration [29–31]. Because we deal with S-CO_2 coal fired power plant, S-CO_2 nuclear, solar or gas turbine power plants are not commented one by one here.

When S-CO_2 cycle is used for coal fired power plant, the thermal coupling between boiler and cycle is a major issue. S-CO_2 coal fired power plant is in concept design stage. Moullec [32] and Mecheri et al. [33] noted higher thermal efficiency of S-CO_2 cycle compared with water-steam Rankine cycle, even considering post-combustion carbon capture process (CCS) [32,34,35].

For a similar power capacity, the CO_2 mass flow rate shall be several times of a water-steam Rankine cycle [32,36]. The boiler pressure drop becomes ultra-large if a conventional boiler design is used, which is the first challenge to be overcome. The second challenge is how to recover residual flue gas heat in boiler tail flue. In a boiler, the flue gas temperature covers a wide range from 120 °C to 1500 °C, in which the ~120 °C limit is specified by the finally discharged flue gas temperature. A single S-CO_2 cycle cannot absorb heat from heat source in such a wide temperature range. Usually, an air preheater is installed in boiler tail flue to absorb part of residual flue gas heat. When the amount of residual heat is large, using air preheater alone not only introduces an ultra-large air preheater size, because the heat transfer coefficients of both air and flue gas are small, but also causes safety issue for power plant, because the high temperature air may cause “explosive burning” in furnace [37]. Some researchers [32,33,38–40] added an additional heat exchanger called flue gas cooler (FGC) in boiler tail flue to absorb part of residual flue gas heat. A CO_2 flow stream is extracted from total CO_2 flow rate at the outlet of main or auxiliary compressor. Then, the CO_2 stream after being heated by FGC is returned to S-CO_2 cycle. This method can be called the FGC method.

Because the outlet flue gas temperature discharged to environment is decreased by using FGC, the boiler efficiency is increased. However, because an additional heat is added to the cycle, the cycle thermal efficiency is decreased. We note that the power generation efficiency is the outcome of cycle thermal efficiency and boiler efficiency. There is a tradeoff between boiler efficiency and cycle thermal efficiency. Here, the FGC method is revisited, it is found that there exists the efficiency potential to be explored. One may ask a question that if it is possible to maximize both the cycle thermal efficiency and the boiler efficiency simultaneously. Inspired by this question, the “*three/four temperature regimes*” is proposed for cascade utilization of flus gas energy over full temperature range. The top cycle, bottom cycle and air preheater absorb flue gas heat in high, moderate and low temperature regime, respectively. Thus, the separate-top-bottom-cycle is established. A specific running parameter is carefully selected so that it can be varied over a wider range but has less effect on cycle performance. Thus, the total flue gas energy is reasonably distributed among top cycle, bottom cycle and air preheater to ensure better performance of both the top and bottom cycles. Finally, the “*parameter coordination principle*” is proposed to combine the two cycles into one to simplify the whole system design. Our results show that the connected-top-bottom-cycle (CTB) apparently improves performance compared with supercritical water-steam Rankine cycle power plant.

This paper is organized as follows. Section 2 describes the cycles for cascade utilization of flue gas energy, including RC + DRH + FGC (recompression cycle + double reheating + FGC) shown in Section 2.1