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Comprehensive investigation of process characteristics for oxy-steam combustion power plants

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A B S T R A C T

Oxy-steam combustion, as an alternative option of oxy-fuel combustion technology, is considered as a promising CO_2 capture technology for restraining CO_2 emissions from power plants. To attain its comprehensive process characteristics, process simulation, thermodynamic assessment, and sensitivity analysis for oxy-steam combustion pulverized-coal-fired power plants are investigated whilst its corresponding CO_2/O_2 recycled combustion (oxy-CO_2 combustion) power plant is served as the base case for comparison. Techno-economic evaluation and integration with solar parabolic trough collectors are also discussed to justify its economic feasibility and improve its thermodynamic performance further, respectively. It is found that oxy-steam combustion exhibits better performance than oxy-CO_2 combustion on both thermodynamic and economic aspects, in which the cost of electricity decreases about 6.62% whilst the net efficiency and exergy efficiency increase about 0.90 and 1.01 percentage points, respectively. The increment of oxygen concentration in oxidant (20–45 mol.%) and decrease of excess oxygen coefficient (1.01–1.09) in a certain range are favorable for improving oxy-steam combustion system performance. Moreover, its thermodynamic performance can be improved when considering solar parabolic trough collectors for heating recycled water, even though its cost of electricity increases about 2 $/(MW h).

1. Introduction

To mitigate the greenhouse effect on climate change, carbon capture and storage (CCS) technology is proposed as an effective and attractive method for restraining anthropogenic CO_2 emissions from power plants. Oxy-fuel combustion, one of three main CCS technologies, is considered as a technically feasible and economically competitive pathway for capturing CO_2 from coal-fired power plant [1]. Based on different diluents, it can be divided into CO_2/O_2 recycled combustion (oxy-CO_2 combustion) and steam-moderated oxy-fuel combustion (oxy-steam combustion), in which their combustion atmospheres are CO_2/O_2 and H_2O/O_2, respectively. Compared with oxy-CO_2 combustion, oxy-steam combustion is simple, compact and easy to start up and shut down since recycled flue gas is omitted or/and smaller amount of condensed water is recycled. Moreover, the major and auxiliary equipment of the system can be greatly downsized, NOx and SOx formation can be reduced, and the power consumption for recycling condensed water can be saved. Therefore, oxy-steam combustion is considered as the 3rd generation oxy-fuel combustion for capturing CO_2 emission from power plants [2].

In order to obtain process characteristics of oxy-steam combustion, researches on its experiment and simulation have been conducted. Richards et al. [3] used an idealized perfectly stirred reactor and plug flow reactor model (PSR/PFR) simulated in Chemkin-II to identify the residence time requirements and equilibrium CO levels of two oxy-combustion routes, and investigated actual performance on a diluted oxy-fuel combustor. The results showed that the residence time was 5–7 times greater and the equilibrium CO levels were higher for the oxy-CO_2 combustion when compared with that diluted by H_2O. And actual CO levels were higher than equilibrium in oxy-steam combustion because lower excess oxygen was applied to experiment. Salvador et al. [2] proposed burner design for oxy-steam combustion and conducted corresponding experiment in a 0.3 MW_{th} oxy-fuel vertical combustor research facility. It was found that oxy-steam combustion results in lower CO level, moderate NOx, typical SOx, and 5–10% boosting CO_2 concentration. Zou et al. [4–6] conducted a series of studies on its combustion and ignition. A numerical simulation was first carried out to investigate the chemical effects of steam on temperature in methane oxy-steam combustion,

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Nomenclature

Abbreviations

AH	air heater
ASU	air separation unit
CCS	carbon capture and storage
CPU	compression and purification unit
ECO	economizer
EES	Engineering Equation Solver
ESP	electrostatic precipitator
FD	forced draft fan
FGC	flue gas cooler
FGD	flue gas desulphurization
HP	high pressure steam turbine
ID	induced draft fan
IP	intermediate pressure steam turbine
IT	total investment cost
LHV	low heating value
LP	low pressure steam turbine
OM	operation and maintenance cost
PC	pulverized-coal-fired
PFR	plug flow reactor
PSR	perfectly stirred reactor
RF	recycled fan
RH	reheater
RP	recycled pump
SCR	selective catalytic reduction
SPTCs	solar parabolic trough collectors

Scalars

C, c	cost and unit cost
E, e	emission (or exergy) and emission amount
H,h	annual operation hours and enthalpy
M, m	mass flow rate and unit mass flow rate
N	personnel numbers
P	load period
p	O&M coefficient
P_{CaCO_3}	purity of limestone
P_{CaSO_4}	purity of gypsum
p_{fa}	fixed assets formation percentage
p_{ia}	intangible and deferred assets percentage
p_{loan}	load percentage
p_{lv}	residual value percentage
p_m	material cost ratio
p_o	other costs ratio
r_{CO_2}	CO_2 capture efficiency
r_w	welfare and labor insurance coefficient
S	size
T	pollutant emission tax
v	unit volume
W	power
Y_d	depreciation period

Greek letters

η	efficiency/exergy efficiency
ξ	Average interest rate

Subscripts

0	base (air combustion) plant
2	oxy-steam combustion
ar	as-received basis
b	boiler
CAC	CO_2 avoidance cost
CCC	CO_2 capture cost
COE	cost of electricity
F	fuel
N	NOx
net	net power output
O	oxygen
P	product
pay	payment
pw	process water
S	SOx

concluded that steam concentration in oxidant should be 72.5 mol.% to match temperature profile in air-combustion. Additionally, the chemical effects on flame temperature and key element reactions would be distinctive when steam mole fraction range changes. Then, the combustion characteristics of two different pulverized coals in H_2O/O_2 mixtures and the effects caused by variations of combustion atmosphere, oxygen concentration, heating rate and particle size were also investigated. Further, experiments on a drop tube furnace under different oxygen fractions (21%, 30%, 35%, 40% and 50%) were executed to identify the ignition behavior of coal in N_2/O_2 and H_2O/O_2 atmospheres. At the identical oxygen concentration, the ignition of pulverized coal in the H_2O/O_2 atmospheres occurred sooner than in the N_2/O_2 atmospheres. A high concentration of steam may enhance the steam gasification reaction and steam shift reaction in H_2O/O_2 atmospheres, which would be beneficial to reducing the ignition delay times of volatiles mixtures. Based on the previous study [6], Cai et al. [7] further analyzed the effects of the physical–chemical properties of H_2O on the ignition of coal under oxy-steam combustion by numerical simulation, showed that the steam shift reaction is the primary reason for the advanced ignition of coal in the H_2O/O_2 atmospheres while the steam gasification reaction is a minor reason for the phenomenon. On the process simulation front, Seepana and Jayanti [8] presented flame structure analysis for determining oxygen concentration to get a stable combustion and thermodynamic analysis to compare it with corresponding air-combustion. It was concluded that oxygen concentration in oxidant should be 36% by mass and net efficiency penalty would be 8 percentage points. Sheng et al. [9] compared the thermodynamic performance of oxy-CO_2 combustion and oxy-steam combustion in terms of process simulation and exergy analysis, and suggested that the net efficiency of oxy-steam combustion decreases by 0.15 percentage points compared to oxy-CO_2 combustion with the same boundary conditions since the corresponding main steam and reheated steam mass flow rates reduces by 0.84%, and the system exergy efficiency of oxy-steam combustion was 0.153 percentage points lower than that of oxy-CO_2 combustion, due to the increased exergy destruction occurred in oxy-steam combustion furnace. These studies promoted the understanding of oxy-steam combustion.

However, few researches have been conducted to identify its macroscopic aspects like effects of operating parameters on system performance, economic feasibility, and technical integration. Researching on these process characteristics can obtain significant information for process design and operation, which would then be helpful for spreading the application of oxy-steam combustion technology. This paper is organized as follows. In Section 2, the description for studied oxy-steam power plant and steady-state process modeled in Aspen Plus (version 7.1) are presented. Then, detailed energy and exergy analyses for comparisons of the thermodynamic performance between oxy-steam combustion and