Simulation and Exergy Analysis of a 600 MWe Oxy-Combustion Pulverized Coal-Fired Power Plant

Jie Xiong, Haibo Zhao, Meng Chen, and Chuguang Zheng

Abstract

CO_2 emission from pulverized coal-fired power plants (PC) can be efficiently controlled by adopting the oxy-combustion technology, which adds a cryogenic air separation process (ASU) and a flue gas treatment process (FGU) to the conventional combustion process. To understand the thermodynamic properties of the oxy-combustion process, a simulation study and an exergy analysis of a 600 MWe oxy-combustion PC were conducted. The commercial flowsheet software Aspen Plus was used to simulate the process and the simulation results are the basis to perform the exergy analysis. The simulation results show that the CO_2 concentration in the flue gas from the oxy-combustion boiler can be more than 80 mol% and the CO_2 purity from the FGU can reach 99 mol%; the net efficiency of the oxy-combustion system is 10.84% (lower heating value) lower because of the power consumptions of the ASU and FGU processes; the unit power consumption for the oxygen production in the ASU is 0.247 kWh/kg-O_2. The exergy analysis focused on the boiler models (oxy-combustion and conventional) and each of them was divided to be several parts, such as furnace, heat exchanger. The exergy analysis results show that the exergy efficiency of the oxy-combustion boiler is 0.8% higher than that of the conventional combustion boiler, the primary reason for this is the exergy efficiency of the combustion process in the oxy-combustion boiler is about 4% higher. In addition, water wall and air heater in any boiler model have very low exergy efficiencies.

Keywords

Oxy-combustion • Process simulation • Exergy analysis • Aspen Plus

1 Introduction

CO_2 emission has become a global issue, the CO_2 concentration may also reach an unacceptable level even if we could take immediate action [1]. The emission of CO_2 in China had reached about 6.55 gigatons (22.3% of world's CO_2 emission) [2] in 2008. Coal-fired power plants contribute most CO_2 emission in China, because over 60% of the total energy is supplied by that. CO_2 capture and sequestration (CCS) from power plants is a feasible and effective choice, perhaps the only choice, to control the CO_2 emission at the present stage [1], especially for China. Oxy-combustion (or oxy-fuel) technology is such a CO_2 capture approach which can produce high purity CO_2 gas stream through combining a conventional PC with a cryogenic air separation unit (ASU) and a flue gas treatment unit (FGU) (as shown in Fig. 1).

High purity oxygen product (greater than 95% by volume [3]) from the ASU, instead of air, is used as the oxidizer in the oxy-combustion technology, and about 70 – 80% of the flue gas [4, 5] is recycled back to the furnace with the oxygen stream, which could keep the combustion temperature inside

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the furnace within the conventional range by appropriately adjusting the recycle ratio and some other parameters. The resulted flue gases from the furnace consist primarily of CO_2 and water vapor [5] because there is no N_2 dilution during the fuel combustion. The flue gas from the boiler is then cleaned, dried and compressed, followed by separation of noncondensable gases (Ar, O_2 and N_2) from CO_2. Then a 99 mol% CO_2 product could be obtained and finally boosted to pipeline pressure [5]. In comparison to conventional air-fired combustion flue gases, which contain a high N_2 fraction and relatively low CO_2 fraction (13 – 15% by volume) [6], the CO_2-enriched flue gas from the oxy-combustion process is obviously less energy-demanding.

System process simulation is an effective tool to understand the thermodynamic properties and adjust operation conditions of oxy-combustion systems. Moreover, the simulation results are an indispensable basis to do a more sophisticated thermodynamic analysis, such as exergy analysis, and even optimization. Some commercial flowsheet softwares such as Aspen Plus, Thermoflex, and Hysys are usually used to study thermodynamic and chemical processes. Aspen Plus is considered to be a proper tool to study the oxy-combustion technology and some works about that have been published [5, 7]. To better understand the thermodynamic characteristics of the oxy-combustion technology and find out its inefficient sources for further optimization, an exergy analysis on the oxy-combustion system is very necessary, which is presented in this paper.

Exergy is an important concept in the thermodynamics, it is defined as "the maximum theoretical useful work (shaft work or electrical work) obtainable as the systems interact to equilibrium, heat transfer occurring with the environment only" [8]. Exergy analysis focuses on the quality of energy but not the quantity of energy. Therefore, the exergy analysis is usually carried out to determine the magnitudes, locations and types of exergy losses occurring in the system [9] and in this situation, there will be a guideline for reducing the inefficiencies, saving energy consumptions and optimizing the system. Not surprisingly, the exergy analysis has been widely used to study different thermodynamic systems.

To find out the superiorities or drawbacks of the oxy-combustion technology in comparison to the conventional combustion, an exergy analysis of the boiler models was conducted. In this paper, a 600MWe supercritical PC which is typical in China was chosen for analysis. First, Aspen Plus, Version 7.1, was used to simulate the oxy-PC fueled by Shenhua coal (shown in Sect. 2). Then the exergy analysis on the boiler models (shown in Sect. 3) was carried out based on the simulation results and exergy calculation methods. In the exergy calculation process, physical exergy and chemical exergy of each stream in both models were all calculated and moreover, material streams were divided to be different phases for more accurate results.

2 Process Simulation

A Schematic diagram of the oxy-combustion technology is shown in Fig. 1. The oxy-PC studied in this paper includes four sections: boiler, turbines & feed water heaters (FWHs), ASU and FGU.

For the boiler model, there is no component corresponding to "Coal" in the Aspen Plus component library and it is defined as a Non-conventional component. The raw coal is decomposed to be each element (e.g., H_2O, ASH, C, H_2, N_2, Cl_2, S, O_2) contained in the coal, and then combusted in the furnace with recycled flue gas and pure oxygen from ASU. The flue gas goes through the super-heater (SH), re-heater (RH), economizer (ECO), air Heater (AH), electrostatic precipitator (ESP), flue gas desulphurization (FGD) as well as water dryer, and then about 70% flue gas is recycled back into the furnace. It is a pair of HEATER blocks used to model the SH, RH, ECO and AH in Aspen Plus. SO_x and water is assumed to be removed completely in the FGD and water dryer, respectively; and it is assumed that there is 2% air ingress in the furnace.

There are four blocks in the ASU simulation: multistage compressor (MCOM, unit 1 and 2), heat exchanger (HEX, unit 3), distillation column (COLUMN, unit 4) and expansion valve (unit 5). In the MCOM, a configuration of four stages with intermediate cooling was devised. In the column, the bottom product is liquid O_2 and the top product is vapor N_2. Obviously, there are some impurities in each product and the O_2 concentration is designed to be great than mol 95%.

In the FGU process, flue gas is cleaned, compressed, dried and distillated to obtain the pure CO_2. As a first step, flue gas is flashed with cooling water in a flash evaporator. And then, it is compressed to 3 Mpa in a three stages compressor with intermediate cooling. The remaining water is removed by another flash evaporator. After flowing through the heat exchanger, the flue gas is distillated in the column. The CO_2 product (bottom) purity is designed to be 99%.

Three kinds of chemical property were utilized in the simulation: PR-BM for the section boiler; STEAMNBS for the section turbines & FWHs; and PENG-ROB for the section ASU and FGU.

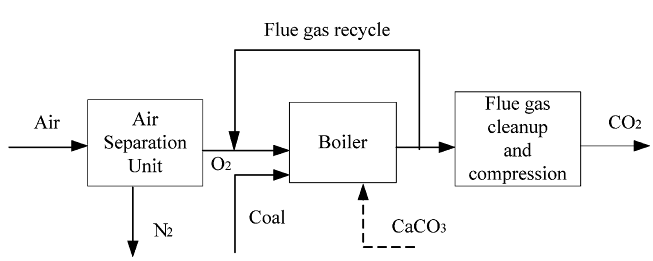

Fig. 1 Schematic diagram of Oxy-combustion

Table 1 Proximate analysis and ultimate analysis of coal (as-received basis)

Proximate Analysis (wt%)		Ultimate Analysis (wt%)	
Moisture	13.8	C	60.51
Volatile Matter	26.2	H	3.62
Ash	11	O	9.94
Fixed Carbon	49	N	0.7
LHV (kJ/kg)	22,768	S	0.43

Table 2 Basic inputs needed in the simulation

Item	Value
SH steam	598.89°C, 242.35 bar,469.5 kg/s
RH steam	621.11°C, 45.09 bar
O_2 excess factor	1.05 [10]
Furnace outlet	1,100°C, 1 atm
Recycle ratio	0.695
Air ingress	15°C, 1 atm, 2% of total gas supplied into the boiler
Condenser outlet	38.74°C, 0.368 bar
Turbine stage discharge pressure (HP1–LP5), (bar)	77.07, 49.02, 21.36, 9.515, 5.013, 1.323, 0.5771, 0.2473, 0.0689
TTD (FWH1-7), (°C)	−1.111, 0, −1.111, 2.778, 2.778, 2.778, 2.778
Generator efficiency	98.58%

The proximate analysis and ultimate analysis of the Shenhua coal are listed in Table 1. In the table, all data are on the as-received (ar) basis, C, H, O, N and S mean carbon, hydrogen, oxygen, nitrogen and sulphur in the coal, respectively; LHV is the lower heating value of the raw coal. Moreover, some basic inputs needed in the simulation, such as turbine heat balance, are given in Table 2. The simulation results show that the net efficiency is 10.36% lower due to the ASU and FGU processes and the unit power consumption for oxygen production is 0.247 kWh/kg-O_2.

3 Exergy Analysis

3.1 Exergy Calculation Methods

Exergy means a measure of the departure of the system state from the environment state. Exergy is also the measure which coordinates quality with quantity of energy. The total exergy (E) can be divided into four parts: physical exergy (E^{PH}), kinetic exergy (E^{KN}), potential exergy (E^{PT}) and chemical exergy (E^{CH}), which can be described as [8]:

$$E = E^{PH} + E^{KN} + E^{PT} + E^{CH} \quad (1)$$

The E^{KN} and E^{PT} are relating to velocity and elevation, respectively, so in a thermodynamic system, such as the coal-fired power plants analyzed in this paper, they could not be taken into consideration. There are just the E^{PH} and E^{CH} left for calculation. Generally speaking, the E^{PH} arises from the temperature and pressure differences between the system analyzed and the environment; and the E^{CH} arises from the composition difference. The calculation methods and equations about the E^{PH} and E^{CH} are introduced as follows.

Table 3 Definition of the environment model

Temperature T_0	298.15 K		
Pressure P_0	1 atm		
Component			
Gaseous phase	Mole fraction	Condensed phases (T_0, P_0)	State
N_2	0.7567	H_2O	Liquid
O_2	0.2035	$CaCO_3$	Solid
H_2O	0.0303	$CaSO_4 \cdot 2H_2O$	Solid
Ar	0.0091		
CO_2	0.0003		

First of all, an environment state should be defined for the exergy calculation. The state contains not only the temperature and the pressure, but also the chemical components of the environment. An appropriate environment model [11] is given in Table 3.

With the definition of the environment model, each kind of exergy could be calculated by the equations presented as below.

For the unit physical exergy [8] (e^{PH}, kJ/kmol):

$$e^{PH} = \Delta h - T0\Delta s = (h - h0) - T0(s - s0) \quad (2)$$

here h and s mean unit enthalpy (kJ/kmol) and unit entropy (kJ/(kmol·K)), respectively. And the subscript "0" means the reference state.

For the chemical exergy calculation of a mixture material stream, gaseous mixture and non-gaseous mixture are treated differently. In detail, for a gaseous mixture, its e^{CH} can be calculated by [8]:

$$e^{CH} = \sum x_k e_k^{CH} + RT0 \sum x_k \ln x_k \quad (3)$$

in which x_k means the mole fraction of the gaseous component in the mixture stream. And for a non-gaseous mixture, its e^{CH} is the weighted sum of unit chemical exergies of all components in the mixture.

There is another special material, coal. The chemical exergy calculation of coal is more difficult and there are some empirical equations exist. The detailed chemical exergy calculation process of coal can be found in the reference [8, 12] and that was adopted in this paper. Then the e^{CH} of the Shenhua coal can be calculated to be 24686.6 kJ/kg (ar). It is worth noting that the e^{CH} of a coal sample nearly equals its higher heating value [8, 12].

3.2 Exergy Analysis of Boiler Models

For oxy-combustion boiler or conventional boiler, there are two main parts for each boiler model:furnace (FUR) and heat exchangers (HEXs). And the HEXs include convective super-heater (CSH), radiation super-heater (RSH), RH, ECO, water wall (WW) and AH. Coal is combusted with oxygen in the FUR and the E^{CH} of coal is converted to be E^{PH} as radiation heat and convection heat. Then the heat is absorbed by the feed water or steam to drive the steam turbines and so generate the power.

Based on the simulation results and exergy calculation methods introduced above, an exergy analysis work was performed to the two boiler models. Then, exergy efficiency (η_{ex}) of each unit or even the whole system can be calculated out. H_{ex} is also called second law efficiency, effectiveness or rational efficiency, and is usually defined as utilized exergy divided by provided exergy [8, 13]. Since there are many kinds of definition to the "utilized exergy" and the "provided exergy", so there are lots of different exergy efficiency definitions [13]. In this paper, the η_{ex} is defined as the ratio of product (P) to fuel (F), which is illustrated as Eq. 4 [14]:

$$\eta_{ex} = E_P/E_F \tag{4}$$

where E_P and E_F are exergies from product and fuel, respectively. Usually, each device has its own productive purpose, such as steam for the boiler and power for the generator. The productive purpose of a process device measured in terms of exergy is named as "product"; and the consumed exergy flow to create the product is "fuel" [15, 16]. Therefore, it is important to define the F and P for each unit in the systems and F-P definitions about some important thermodynamic devices can be found in refs [8, 17].

Some η_{ex} definitions about units in this paper are described as follows:

$$\text{FUR}: \quad \eta\text{ex,FUR} = \left(E^{PH}_{Rad} + E_{G3}\right)/\left(E_{G2} + E^{CH}_{C1}\right) \tag{5}$$

$$\text{HEX}: \quad \eta\text{ex,HEX} = E^{PH}_{A}/E^{PH}_{S} \tag{6}$$

$$\text{and boiler}: \quad \eta\text{ex,B} = E^{PH}_{A,FW}/\left(E^{CH}_{C1} + E_{G1} - E_L\right) \tag{7}$$

in Eq. 7, E_L includes exergy losses of flue gas, ash and radiation; subscript "FW" means feed water.

Based on the exergy calculation results and η_{ex} calculation equations defined above, the η_{ex} calculation results for the two boiler models are given in Table 4. The results show that the η_{ex} of the oxy-combustion boiler is 0.8% higher than that of the conventional combustion boiler; exergy efficiencies for the FG-FW heat exchange process in the two boiler models are nearly equivalent, however, the $\eta_{ex,FUR}$ in the oxy-combustion system is much higher, about 4%, than that in the conventional combustion system. And that should be the primary reason why the oxy-combustion boiler performs higher exergy efficiency.

Table 4 Exergy efficiency calculation results for boiler models

Item	Oxy-boiler (%)	Conventional boiler (%)
FG-FW heat exchange	75.7	76.0
FUR	75.4	71.5
Whole boiler	51.4	50.6
ECO	83.9	84.4
WW	69.5	69.4
RSH	75.1	74.4
CSH	79.4	80.0
RH	84.6	85.7
AH	66.2	55.9

The FG-FW heat exchange process relates five HEXs: WW, RSH, CSH, RH as well as ECO, and WW has the lowest exergy efficiency among the five HEXs. Moreover, the exergy efficiency of AH is even lower than that of WW, the heat exchange process in AH occurs between flue gas and inlet gas. The $\eta_{ex,AH}$ in the oxy-combustion system is 10.3% higher than that in the conventional combustion system.

4 Conclusion

An oxy-combustion pulverized coal-fired power plant system including an ASU and an FGU was simulated in a Aspen Plus platform. The simulation results show that CO_2 concentration in the flue gas from boiler can be more than 80% and the purity of the CO_2 product from FGU can reach 99%. The net efficiency is 10.36% lower due to the ASU and FGU processes and the unit power consumption for oxygen production is 0.247 kWh/kg-O_2.

Based on the simulation results, an exergy analysis of the boiler models was performed. The results for the boiler models show that the exergy efficiency of the oxy-combustion boiler is 0.8% higher than that of the conventional combustion boiler, the primary reason for this is the furnace exergy efficiency in the oxy-combustion boiler is about 4% higher. Moreover, water wall and air heater in each model have very low exergy efficiencies. And because of the flue gas recycle in the oxy-combustion boiler, the exergy efficiency of the air heater in the oxy-combustion system is 10.3% higher than that in the conventional combustion system.

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