Chapter 1

Introduction

1.1 Overview

This chapter presents the motivation of the current study by enlisting both opportunities and challenges of coal combustion. A brief discussion of various carbon capture and sequestration (CCS) technologies has been addressed. The key differences between oxy-fuel combustion and the conventional air combustion have also been discussed. Furthermore, contributions and thesis structure have been provided in the last part of the chapter.

1.2 Motivation

Coal is the most abundant energy source and plays a vital role in power production worldwide (Franchetti et al., 2016). It is supposed that the need for power production will grow in upcoming decades as population tends to increase, which will increase the demand for electricity by the use of more electrically powered devices. Coal will continue being the dominant energy production source due to its abundant reserves and lower competitive price (Chen et al., 2012). Although considerable efforts are being made to substitute the coal by renewable energy sources (e.g., solar, wind, biomass, etc.), but, expansion of these technologies on a global scale will take time. Renewable energy sources can only supplement conventional technologies in the near future (Toporov, 2014). Moreover, the high risks associated with the usage of nuclear power as an energy production source have contributed to an increasing lack of recognition of this technology by many communities (Franchetti et al., 2013).

The key problems that coal faces are its environmental effects, both in terms of production and usage. Nowadays, pulverized coal (PC)-fired power plants show high reliability and availability and are much cleaner than ever before (Heil et al., 2009). Emissions of NO_x, SO_2 and particulate matter was decreased by more than 90% in many older plants relative to unregulated rates. This is done through sophisticated combustion and back-end cleaning technologies.

More recently, greenhouse gas (GHG) emissions, including carbon dioxide (CO_2) emissions, have become a problem owing to their potential connection to climate change. There is a range of solutions available to reduce CO_2 pollution. Recently, CO_2 capture and storage techniques applied to the coal-fired power has gained tremendous attention as a viable choice that can minimize such emissions significantly. Current research focuses on oxy-fuel pulverized coal combustion due to fast CO_2 recovery and low NO_x pollution.

1.3 Carbon Capture and Sequestration (CCS) Technologies for Coal-fired Power Plants

Increasing concentration of CO_2 is the environmental concern and leading cause of global warming. Only CO_2 itself is responsible for around 60% of global warming. Atmospheric CO_2 concentration can be reduced by (1) utilizing energy more efficiently, (2) utilizing alternative fuel and renewable energy, and (3) CCS technologies. The CO_2 capture and sequestration approaches are: (1) pre-combustion capture (i.e., CO_2 separation is performed prior to combustion process, Jansen et al., 2015; Theo et al., 2016; Valiani et al., 2017); (2) oxy-fuel combustion capture (i.e., CO_2 separation is performed during combustion under O_2 rich environment instead of air, Lasek et al., 2013; Wu et al., 2018; Yin and Yan, 2016); (3) post-combustion capture (i.e., CO_2 separation is performed after the combustion process, Cormos and Cormos, 2017; Dinca et al., 2018; Ferrara et al., 2017).

International Energy Agency (IEA) claimed in its roadmap that 20% of the total CO_2 emission would be removed through CCS by 2050 (Al-Qayim et al., 2015). Many authors reported that all CCS methods result in reduced plants efficiency (Escudero et al., 2016; Scheffknecht et al., 2011). Pre-combustion and post-combustion capture results in the decrease of plant efficiency by around 8% to 12%, whereas in oxy-fuel combustion capture plant efficiency reduction (around 7%-11%) is little low due to heat integration and process optimization. CCS technologies are very expansive and lack its application in industrial units. The capture of CO_2 is the most expansive part of CCS and accounts for around 75% of the total CCS cost.

1.4 Oxy-Fuel Combustion for Carbon Capture and Sequestration (CCS)

According to the recent report of international energy agency (IEA,2019), coal-fired power plants fulfil 38% of global power requirements and are responsible for 30% of global CO_2 emission (IEA, 2019). According to the report, global coal demand has been increased by 0.7% in 2018, which is slower than the last decade’s (2000-2010) annual growth report of 4.5%. Although the share of coal in primary energy demand and power generation continues to decline slowly, it still remains the largest source of electricity and second largest source of primary energy (IEA,2019). Therefore, it is necessary to attain the emission reduction targets of coal fired power plants. During the past few years, the combustion of fuel under oxy-fired combustion environment has gained a lot of attention due to the capability of CO_2 capture (Farooqui et al., 2018). The schematic diagram of oxy-coal combustion is shown in Fig. 1.1. In oxy-fuel combustion pure oxygen (having around 95% purity) and recycled flue gas (RFG) is used for combustion. Recycled flue gas (RFG) works as diluents and controls the flame temperature in the oxy-fired power plant. The exhaust gas generated has mainly CO_2 and water vapor. The highly concentrated CO_2 can be easily separated by condensing water vapor. Oxy-fuel combustion has an unstable flame, delayed flame ignition, low flame temperature, changed heat transfer, and decreased NO_x and SO_x emission than the air combustion. These differences in performance of oxy-fuel combustion are due to different properties of CO_2 than N_2, as shown in Table 1.1.

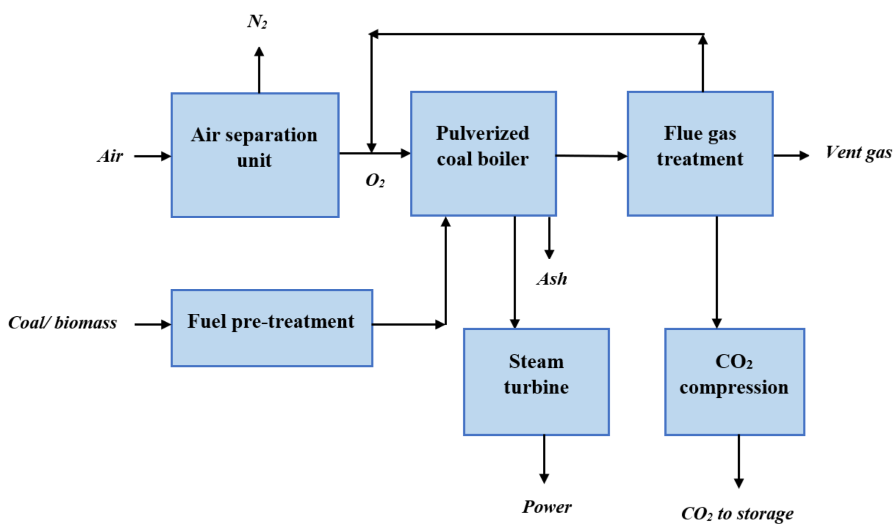

Fig. 1.1. Schematic diagram of oxy-fuel combustion based CCS (adapted from Cormos, 2016)

Table 1.1 Gas properties for N_2 and CO_2 at 1173 K (Toporov, 2014; Yin and Yan, 2016)

Property	**N_2**	**CO_2**	**Ratio CO_2/N_2**
Thermal conductivity (W/m-K)	0.07467	0.08169	1.09
Molar heat capacity (kJ/kmol-K)	33.6	56.1	1.67
Density (kg/m^3)	0.29	0.45	1.55
O_2 diffusion coefficient (m^2/s)	3.074e-04	2.373e-04	0.77
Thermal diffusivity (m^2/s)	2.167e-04	1.420e-04	0.65
Molecular weight (kg/kmol)	28	44	1.57
Energy per volume (J/m^3-K)	0.34	0.57	1.67

CO_2 has a higher molar heat capacity than N_2; thus, CO_2 can work as a better heat sink than N_2. It is the main reason behind reduced flame temperature in the oxy-fuel environment. CO_2 has higher molecular weight than N_2, which results in the highly-dense flue gas in oxy-fuel conditions and causes lower gas velocity and higher residence time of particles in the furnace. Slower flame propagation speed in the oxy-fuel condition is due to the lower thermal diffusivity of CO_2. The combustion gases have a lower temperature under oxy-fired conditions than the air-fired conditions at identical O_2 content due to higher energy per volume of CO_2. The RFG has a high partial pressure which causes higher flue gas emittance. Thus, to obtain identical radiative heat transfer in boiler retrofitted to oxy-fuel, O_2 content should be less than the required levels for the same AFT in O_2/RFG passing through the burner.

1.5 Contributions

The main focus of this study is the computational analysis of oxy-coal combustion. After the validation of the developed numerical model with the available experimental data, the numerical investigations of important operating parameters on the flow field, thermo-chemical (temperature and species concentration) and radiative quantities have been performed. The NO_x emission under oxy-coal combustion has been investigated employing post-processing solution techniques. Furthermore, we have extended the oxy-coal combustion concept and performed the thermodynamic analysis of 660 MW supercritical power plant retrofitted to oxy-coal combustion. Energy penalty of oxy-coal combustion-based CCS along with CO_2 product purity and CO_2 recovery rate has also been accessed. The major objective of the thesis can be classified as:

1. To develop a numerical model of oxy-pulverized coal combustion in tubular combustor and validation of the developed numerical model with the available experimental data.
2. Numerical investigation of the influence of swirl strength, combustion environment, inlet temperature and pressure of feed gas on the flow field and combustion characteristics.
3. Study of the temporal variation of particle-phase variables such as particle temperature, particle volatile and particle char mass fraction under oxy-coal combustion conditions.
4. Numerical investigation of the influence of higher concentration steam addition on oxy-coal combustion process and comparison of ideal dry recycle oxy-coal

combustion case with wet oxy-coal combustion cases (10-50% H_2O) and oxy-steam combustion case (H_2O replaces CO_2 in the oxidant).

5. Study the influence of char gasification reactions on temperature profile and species concentration under oxy-coal combustion atmosphere.
6. Numerical investigation of influence of the above-mentioned parameters on NO_x emission under oxy-coal combustion atmosphere.
7. Thermodynamic analysis of 660 MW pulverized coal-fired power plant retrofitted to oxy-coal combustion and comparison of retrofitted oxy-coal combustion power plant with the conventional air-fired power plant.

1.6 Thesis Structure

The present study is distributed in seven chapters, and outlines of the chapters are mentioned briefly. Chapter 1 provides the introduction of oxy-coal combustion, its advantages and limitation compared to conventional air fired combustion. Detailed literature review on oxy-coal combustion focussing on fundamental aspects of pulverized coal combustion under oxy-coal combustion conditions has been presented in Chapter 2. The difference between conventional air-fired combustion with the oxy-coal combustion has been discussed. Both wet and dry recycle oxy-coal combustion have been thoroughly reviewed and compared in this chapter. In the last section of the chapter, we have reviewed the work focussing on oxy-coal combustion-based carbon capture and storage (CCS) techniques in large scale power plants. Chapter 3 has been divided into two parts. In the first part of Chapter 3 detailed discussion on numerical modelling of oxy-coal combustion along with employed models/submodels is presented. In the second part of Chapter 3, grid independence study and experimental validation of the developed numerical model has been presented. The numerical investigation results of oxy-coal combustion have been provided in Chapter 4 and Chapter 5. Chapter 4 summarizes the influence of swirl strength, combustion environment, inlet temperature and pressure of feed gas on the flow field and combustion characteristics. Chapter 5 presents the influence of higher concentration steam addition on the oxy-coal combustion process. Chapter 5 also investigates the influence of gasification reactions on temperature profile and species concentration employing the developed numerical model. In the last part of the chapter, NO_x emission under oxy-coal combustion atmosphere has been computed. Chapter 6 presents the thermodynamic analysis of 660 MW supercritical pulverized coal-fired power plant retrofitted to oxy-coal combustion. The energy penalty, CO_2 product purity and CO_2 recovery rate of the oxy-coal combustion power plant have been estimated. Furthermore, sensitivity analysis has been performed in this chapter to identify important operating parameters.

Chapter 7 summarizes the key conclusions from the thesis and provides recommendations for future work.