OXY-COAL COMBUSTION: STABILITY OF COAXIAL PULVERIZED COAL
FLAMES IN O₂/CO₂ ENVIRONMENTS

by

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ABSTRACT

Oxy-coal combustion, in which air is replaced by an $\text{O}_2/\text{CO}_2$ mixture, is one of the few technologies that may allow $\text{CO}_2$ capture and sequestration technologies to be applied to existing coal-fired boilers. One issue of interest is to understand and predict the effects of near-burner-zone environment, now consisting of $\text{O}_2$ and $\text{CO}_2$ instead of $\text{O}_2$ and $\text{N}_2$, on flame stability. This dissertation is directed towards understanding how the composition of the coal transport medium (primary $\text{CO}_2$ and $\text{O}_2$) affects the ignition standoff distance in 40kW coaxial turbulent diffusion, oxy-coal flames, supported in a specially designed combustion test rig, rated at 100kW. The focus is on mechanisms of interaction between turbulent mixing in coaxial jets and coal particle ignition, rather than on each physical or chemical process taken individually. Experimental data focus on flame stability for a Utah Bituminous coal, although fragmentary results for a Powder River Basin (PRB) coal are also presented. Design considerations for the experimental rig and coal feeding system used are described in detail, and, because the emphasis was on flame stability under steady flow conditions, great care was exercised to demonstrate steady coal feeding behavior.

A methodology to define and quantify the ignition behavior of laboratory-combustor-scale turbulent pulverized coal jets is developed and is described in detail. Flame stability is quantified by standoff distance, which is the distance between the burner tip and ignition point, and is defined by 6000 flame images obtained at the camera
(EPIX SV5C10 CMOS) settings of 8.3 ms exposure time and 30 frames per second, which can correlate with the observations of human eyes and provide a physical description of a coaxial pulverized coal turbulent flame. Results are presented in the form of probability density function profiles of the measured standoff distance, as obtained from replicate runs, each consisting of 6000 photo images.

Results show that flame stability is affected by primary $P_{O_2}$, secondary preheat temperature, secondary $P_{O_2}$, and transport diluent composition. Under certain conditions, multiple stand-off distances were observed for the same inputs. A targeted test, comparing different primary transporting media ($O_2/CO_2$ mixture and $O_2/N_2$ mixture), provided additional insight into flame stabilization under oxy-coal combustion.

Taken together, the results led to the following inferred mechanisms:

1) At constant jet mixing aerodynamics, the composition of the primary jet fluid is very important in determining coal-jet stability in coaxial turbulent diffusion jet flames. Increasing primary $P_{O_2}$ always helps stabilize the flame, and in general, primary $P_{O_2}$ must exceed 10 vol% to allow this to occur. Not only is the concentration of $O_2$ in $CO_2$ important, but also the diluents containing the oxygen ($CO_2$ versus $N_2$). When $CO_2$ is replaced by $N_2$ in the primary jet, the primary jet need not contain $O_2$ to allow stable flames.

2) The composition and the temperature of the secondary jet fluid are also very important. Flame stabilization is very sensitive to changes in secondary flow temperatures, from 489 K to 544 K, with the higher temperature leading to more stable flames. At higher secondary flow $O_2$ concentrations ($\geq 53$ vol%), coaxial oxy-coal turbulent diffusion flames can be stabilized with zero oxygen
in the primary jet, even at lower preheat values. This latter result is of practical importance, since there is often an incentive to minimize contact of O$_2$ with coal in the primary jet.

A mass transfer model is developed to correlate some of the data. The model is based on computing the ignition time by assuming a molecular diffusion controlled mechanism. Data correlate well, which supports the hypothesis that coal particle ignition in turbulent diffusion coaxial jet flames is controlled by molecular diffusion, namely that of O$_2$ through CO$_2$ or N$_2$. This conclusion can help better understand pertinent ignition mechanisms when switching from air-firing to oxy-firing conditions.

These experimental data, together with their uncertainty quantification which is also presented, provide not only qualitative insight into the ignition of coal in turbulent oxy-coal flames of practical relevance, but also a basis for validation of future detailed simulations of this process.
# TABLE OF CONTENTS

ABSTRACT ................................................................................................................................... iii

ACKNOWLEDGEMENTS ........................................................................................................... ix

1. INTRODUCTION ................................................................................................................ 1

1.1 Background ........................................................................................................................ 1
1.2 Single Coal Particle Ignition Mechanism .............................................................................. 3
    1.2.1 Homogeneous versus Heterogeneous ........................................................................ 3
    1.2.2 Ignition Criteria ........................................................................................................... 6
    1.2.3 Factors Influencing Coal Particle Ignition ................................................................. 8
    1.2.4 Ignition Mechanism under Oxy-Coal Combustion Conditions .................................. 10
    1.2.5 Limitations of Single Coal Particle Ignition Mechanism ........................................... 11
1.3 Near-Burner Phenomena Studies ...................................................................................... 13
    1.3.1 Challenges in Near-Burner Phenomena Studies ....................................................... 13
    1.3.2 The Coaxial Jet ........................................................................................................ 15
    1.3.3 Flame Stability ......................................................................................................... 19
1.4 Pollutant Reduction during Oxy-coal Combustion ............................................................ 21
1.5 Summary of Literature Review ......................................................................................... 22

2. SCOPE OF THIS WORK ....................................................................................................... 24

2.1 Motivation ......................................................................................................................... 24
2.2 Objectives and Scope ....................................................................................................... 26

3. EXPERIMENTAL SETUP ................................................................................................. 28

3.1 Reactor Design Criteria .................................................................................................. 29
3.2 Furnace Pictures and Design Schematics ....................................................................... 30
3.3 Burner Zone .................................................................................................................. 34
3.4 Radiant Zone .................................................................................................................. 38
3.5 Convective Zone ............................................................................................................ 38
3.6 Pressure Control System ............................................................................................... 39
3.7 Gas Delivery System ..................................................................................................... 39
3.8 Steady Coal Feeding ..................................................................................................... 41
3.9 Intelligent Control – Opto22 ......................................................................................... 45
3.10 Gas Analyzers .............................................................................................................. 45
3.11 Coal Samples ............................................................................................................... 48
3.12 Furnace Shakedown ..................................................................................................... 49
C. INDIVIDUAL PDF PROFILES FOR ALL THE REPLICATES IN CHAPTER 4 .............. 154
D. UNCERTAINTY QUANTIFICATION .......................................................................................... 203
E. OFC SAFETY OPERATION PROCEDURES ........................................................................ 205
F. CD-ROM OF SUPPLEMENTARY MATERIALS .................................................................. 208
REFERENCES ......................................................................................................................... 209
ACKNOWLEDGEMENTS

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1. INTRODUCTION

1.1 Background

Coal, an inhomogeneous organic fossil fuel, has been utilized by human beings for several centuries. The world currently depends on the use of fossil fuels, especially coal, for its energy supply and will continue to do so for a long time. Coal contributes about 50% of the electricity in the United States. In the state of Utah, this number is even as high as 95%.

Coal is the largest source of energy for the generation of electricity worldwide, as well as one of the largest worldwide anthropogenic sources of carbon dioxide emissions. Climate change, one of the largest environmental challenges of our time, is arguably due to increased carbon dioxide levels in the atmosphere [1]. According to the Kyoto Protocol, Annex I countries must reduce their greenhouse gas emissions by a collective average of 5% below their 1990 levels by 2008-2012. One approach for diminishing CO$_2$ emissions into the atmosphere entails capturing the carbon emissions from fossil fuel combustion units and sequestering them deep in the earth. This is carbon capture and sequestration (CCS) [1]. In a postcombustion process, CO$_2$ capture requires absorption into and subsequent regeneration of an absorbent, usually a solution. One CCS process currently under consideration involves burning coal with relatively pure oxygen, coupled with recycled flue gases, to produce a highly concentrated (up to 95% CO$_2$) flue gas stream, which is suitable for immediate compression to a supercritical state and subsequent transportation and sequestration. This is oxy-fuel combustion, one of the
promising technologies to reduce CO₂ emissions, and one that has attracted world-wide attention [2-12].

Sarofim et al. (2004) have summarized the major scientific questions on oxy-coal combustion in pulverized coal (PC) furnace with a CO₂ recycle in terms of the following issues [13]:

1) Can we predict heat transfer profile [14], fouling, slagging, ash partitioning, and char burnout under oxy-coal combustion conditions?

2) Can we predict ignition/kinetic/aerodynamic interactions at the burner?

3) How much residual N₂, NO, Hg, SO₂, trace metals, etc. can be removed with the CO₂ to be sequestered?

4) From where should the recycled flue gases be taken? Should they be extracted from the flue gas after ash removal, after H₂O removal, or after SO₂ removal, or after any combination of these three?

This work focuses on the second question, related to ignition. To study the coal jet ignition and flame stability, it is very important to understand both the chemistry (such as single coal particle ignition mechanisms, kinetic rates of char oxidation, and so on) and the aerodynamics (such as mixing, particle trajectories, and flow patterns) occurring in the near-burner zone. It is also of interest to study the NOx formation under oxy-coal combustion conditions, because measurements of NOx are achieved with little extra effort as by-products of this work, and because NOx from coal flames is sensitive to flame attachment and flame jet aerodynamics. Therefore, this literature review summarizes the previous studies on: 1) coal particle ignition mechanisms; 2) near-burner phenomena studies and flame stability; and 3) pollutant formation under oxy-coal combustion conditions.
In this chapter, we first summarize results on coal particle ignition mechanisms, then survey available results on near-burner aerodynamic studies and flame stability, and finally, briefly review what is known on pollutant formations under oxy-coal combustion conditions. The chapter then concludes with a succinct summary of the objectives and scope of this dissertation.

1.2 Single Coal Particle Ignition Mechanism

1.2.1 Homogeneous versus Heterogeneous

Over the last decade, there have been numerous studies of coal particle ignition mechanisms both experimentally and theoretically on pyrolysis, oxidation of volatiles and CO, carbon reactions, heterogeneous and homogeneous ignition, and combustion of carbon and coal.

The first question was which mechanism, homogeneous or heterogeneous, can better explain the coal particle ignition?

Essenhigh et al. completed a classical review on coal particle ignition mechanisms in 1980 [15]. Both homogeneous, gas phase ignition (GI), and heterogeneous (HI) mechanisms have been proposed to describe the ignition process. The greatest controversy lies on which mechanism is controlling: devolatilization followed by gas phase ignition (first proposed by Faraday) or gas/solid reaction (whole coal ignition). The heterogeneous reaction involves the direct attack of oxygen on the whole coal particle, not just char, and also removes material, which would otherwise be expelled as volatiles [15, 16]. In the GI mechanism, the initial step is pyrolysis and subsequent ignition of the volatiles (Faraday mechanisms), followed by (heterogeneous) ignition of the char. The heterogeneous mechanism neglects the influence of volatile matter and depends on heat
generation by combustion on the coal surface (either externally or internally), whereas the homogeneous mechanism involves the combustion of evolved volatile matter in the vicinity of the particle with its heating by conduction from the volatile flame [16].

Wall and Gururajan applied analyses of both heterogeneous and homogeneous mechanisms to data obtained in their study and showed that:

1. When the surface oxidation rate of the particle is high, two ignition jumps are observed: the first due to the heterogeneous mechanism and the second due to the homogeneous mechanism [16].

2. Although a flame sheet model for the ignition of a single particle by a homogeneous mechanism predicts the observed particle size dependence of the ignition temperature, it fails to predict the observed oxygen concentration dependence [16].

3. Analysis of the ignition temperature data (at temperatures ranging from 650K-1200K and particle sizes less than 500 µm) to determine the reactivity of coal or char, requires a) the assumption of heterogeneous ignition, b) an assumption on the nature of the product of combustion (generally CO₂ rather than CO), and c) the reaction order with respect to oxygen (if experiments were not performed over a range of oxygen partial pressures) [17].

4. When both surface oxidation (heterogeneous mechanism) and volatile combustion (homogeneous mechanism) are considered to occur simultaneously, surface oxidation dominates the ignition behavior (as far as ignition temperature is concerned) of only small particles, or at high oxygen concentrations [17].
Sun suggested that when weight loss occurs before ignition, it can be assumed that pyrolysis occurs first, so that ignition is homogeneous [18]. On the other hand, when ignition occurs before or at almost the same time as weight loss, ignition can be assumed to be heterogeneous. It is possible that both the heterogeneous reaction and pyrolysis occur simultaneously. However, at the early stage of pyrolysis, it is likely that the volatile matter evolved cannot attain the flammability limit. In this case, it is more likely that the ignition of coal particles occurs earlier than the ignition of volatile matter and also that the heterogeneous reaction removes material, which would otherwise be expelled as volatiles [15]. This situation suggests the HI mechanism. In 1979, Juntgen drew a map of ignition regimes as a function of heating rate and particle size, and suggested that if coal particle size is larger than 100 μm and heating rate lower than 100 K/s, GI mechanism should be applied; otherwise HI is more favored [15], as shown in Figure 1.

![Figure 1. Map of ignition regimes as a function of heating rate and particle size. (Source: Reference [15])](image_url)
Du and Annamalai found that ignition for smaller particles is primarily heterogeneous (HI), followed by secondary homogeneous ignition (SGI). Primary ignition is homogeneous (GI) at high gas temperatures and for larger particles. The boundary separating homogeneous ignition from heterogeneous ignition was estimated using their transient model, which changes with ambient temperature and oxygen concentration. The SGI is obtained for particle diameters below 400 μm at ambient gas temperature of 1500 K and oxygen concentration of 0.23 [19].

1.2.2 Ignition Criteria

Essenhigh and Chen defined the heterogeneous ignition criteria by applying Thermal Explosion Theory (TET) [15, 20]:

\[ Q_{gen} = Q_{loss} \]

\[ \frac{dQ_{gen}}{dT_p} = \frac{dQ_{loss}}{dT_p} \]

where \( Q_{gen} \) is the heat generated (unit: W), \( Q_{loss} \) is the heat loss (unit: W), and \( T_p \) is the particle surface temperature. For a coal particle exposed to an oxidizing environment, ignition is determined by the balance between heat generation at, and heat loss from, the particle surface. Thus, the increased coal particle temperature was found to be controlled by the following factors:

1. Heat transfer from the ambient gas.
2. Radiative heat transfer from the chamber’s walls. Before ignition, the temperature of these walls was low and radiation effects on ignition temperature can be assumed to be negligible [16-18].
3. Heat generated by chemical reaction.
4. Heat loss when the temperature of the particles was higher than that of the ambient gas and chambers’ walls.

Therefore, the key of heterogeneous ignition mechanism study is to find the critical ignition temperature at the particle surface and the critical ignition activation energy [16-18, 21-28].

The modeling of homogeneous ignition of a pyrolyzing particle is much less developed than for the heterogeneous case. Gururajan and Wall et al. determined homogeneous ignition temperature as the gas temperature at which the mass consumption rate of the particle shows a jump, i.e., a transition from a low-temperature regime with little combustion of volatiles in the boundary layer to a high-temperature regime where essentially all volatiles burn [16]. Du and Annamalai used a so-called “adiabatic” criterion such that the ignition occurs when the temperature-distance gradient dT/dx is zero at the particle surface [19]. Yet experimental results show that this spatial gradient is not necessarily zero at the particle surface. In other words, the ignition can happen at a point remote from the surface because the oxygen and fuel are diffusing into each other before ignition. For a single isolated particle, the gradients for both oxygen and fuel can be substantial, and the ignition can be in a very narrow region. While in a cloud, the gradients in the interparticle space can be flattened by the turbulence, and the ignition zone can be quite broad [15].

Another challenge for homogeneous ignition mechanism study is to understand the devolatilization of coal particles, which happens before the homogeneous ignition to provide the volatile needed for the homogeneous gas phase reaction [17, 29-34]. The devolatilization is affected by numerous factors, such as coal type, temperature, residence time, particle size, pressure, oxidant concentration, etc. [35, 36].
Other criteria, such as temperature, pyrolysis rate, local gas phase combustible concentration, reaction rate, heat release rate, heating rate, and spatial concentration distribution of combustibles, have been developed to define the ignition of coal particles [15]. However, these criteria have only been used in application to flame spread in fire research problems. In the problem of coal ignition, theories are still evidently limited to TET and adiabatic conditions as have already been discussed.

Commissaris et al. found CO combustion takes place in a wide zone surrounding the particle and CO can indeed be considered to be the only primary product of heterogeneous reaction at certain temperatures [37]. Zhang et al. developed a moving flame front (MFF) model and an improved moving flame front (IMFF) model, taking into account the effect of CO oxidizing in the boundary layer around the particle and the influence of the finite rate heterogeneous reduction of CO$_2$ during combustion of a carbon particle [38-40]. This model more closely agrees with the experimental data compared with the traditional single-film model, and can be applied to the burnout of coal char particles in a practical PC flame.

1.2.3 Factors Influencing Coal Particle Ignition

The ignition process is influenced predominantly by the following physical and chemical processes: rate of diffusion of gaseous fuel and oxidizer species, coal pyrolysis, diffusion of gaseous products and oxidizer species, and gas-phase reaction of pyrolysis products and oxygen [36]. Smoot and Smith believed that reaction of oxygen on the coal surface was not a major factor in this ignition process [36] while others indentified surface oxidation as very important [15, 19].
Chen, in his heterogeneous model, assumed that diffusion effects can be neglected when applying the above ignition criteria because at relatively low particle temperatures of pulverized coal ignition, the oxidation reaction is kinetically controlled [20]. Yet Karcz et al. found the oxidation rate is controlled by diffusion into pores [24]. Therefore, whether or not diffusion in the model is taken into account, it should be carefully considered.

According to the literature, numerous factors, such as coal properties (type, volatile content, reactivity size, size distribution, etc.) [15, 16, 18, 19, 23, 24, 32, 41, 42], heating rate or rate of energy addition [15, 18, 27, 43], oxygen concentration [17-19, 28, 29, 31, 43], auxiliary gaseous fuels, dust concentration, pressure [18, 21, 26], and nature of the gas flow surrounding the particle [18, 25, 28, 31] may all impact coal ignition.

Critical heterogeneous ignition temperature is inversely related to particle diameter [16, 19, 22], oxygen concentration [16, 19, 22], and the pressure in gas of constant concentration [18, 21, 26]. However, with the same oxygen partial pressure, the ignition temperature increases with total pressure [18]. This can be understood as the ignition temperature increases when oxygen concentration decreases. Changing the particle size, heating rate, and volatile content has the same effect at atmospheric and elevated pressures [18]. It was also suggested that the ignition mechanism may shift from homogeneous to heterogeneous at high pressures [18].

Critical homogeneous ignition temperature was experimentally observed to be inversely related to particle size and oxygen concentration [16]. Yet Boukara reported this temperature decreases with decreasing coal particle size [22]. It is possible that for coal particles, especially bituminous ones with high volatiles, the ignition mechanism can be affected by the volatile devolatilization, which varies for different coal types. This
may be the reason Chen et al. found that the mechanism of bituminous coal was uncertain [20]. The modeling results showed the minimum ambient gas temperature required for homogeneous ignition slightly decreases with an increase in oxygen concentration, while the local homogeneous ignition temperature does not appear to change with oxygen concentration [19]. There are many results which agree the coal particle devolatilization rates increased with increasing oxygen concentration at a given gas temperature [28, 29, 31, 33]. It is believed that caution should be taken when studying the homogeneous mechanisms due to the challenges both on the experimental and on the modeling side.

1.2.4 Ignition Mechanism under Oxy-Coal Combustion Conditions

With the exception of the recent work of Molina and Shaddix [28, 31] and of Hu and Zeng [33, 44], few studies have considered the effects of elevated levels of CO₂ on the ignition of coal particles as present in oxy-coal combustion systems. The different properties of CO₂ in comparison to N₂ have been shown to cause differences in flame and furnace operation parameters such as ignition time and gas temperature profiles.

Molina and Shaddix used a combination of particle statistics and one-color pyrometry to measure the particle temperature and CH radical chemiluminescence as a tool for the detection of flame sheet and ignition regions. Single particle imaging shows that the substitution of N₂ by CO₂ increases the time required for ignition. It also shows that the temperature and size of the diffusion flame of the soot cloud that surrounds the particle are lower and larger, respectively, when CO₂ is used instead of N₂, due to the fact that N₂ has a higher thermal diffusivity than CO₂. They also quantified the characteristic devolatilization time and ignition time and found that ignition occurs at higher oxygen
concentrations, and that the presence of CO$_2$ retards coal and char ignition, but has a negligible effect on the duration of devolatilization [28, 45].

Similar experimental methods and results were also reported by Hu and Zeng [33, 44]. They found that coal devolatilization under a CO$_2$ atmosphere is greatly affected by the CO$_2$ gasification reaction, which leads to a higher mass release [33]. The effect of CO$_2$ gasification is coal-rank-dependent. Meanwhile, reduced oxygen diffusion to the particle surface in CO$_2$ is also important under oxy-coal combustion conditions, which is indicated by the longer ignition delay in CO$_2$ than in N$_2$ [44]. However, the corresponding models regarding the diffusion effects under oxy-coal combustion are very rare up to now.

Detailed knowledge of the effects of CO$_2$ on char reactivity in oxy-coal combustion is important for the accurate determination of char burnout and implementation in predictive combustion models. Yet the corresponding experimental data or modeling is still inadequate.

1.2.5 Limitations of Single Coal Particle Ignition Mechanism

An understanding of single coal particle ignition mechanisms helps to build the foundation of our knowledge in coal combustion. However, the single coal particle ignition mechanism cannot sufficiently elaborate on the real turbulent flames due to certain limitations.

First, the particles injected always contain a size distribution. Therefore, the experimental data result from a range of oxidation rates. Thus, the assumption of a single particle size cannot explain some aspects of the experimental results (e.g., the “curvature” of the burn-off curve) and may lead to significant deviations in calculated kinetics
parameters. Only Ballester and Jimenez took the particle size distribution into account [41]. Chen accounted for particle-to-particle variations in reactivity by having a single pre-exponential factor and a Gaussian distribution of activation energies among the particles [20].

Second, the interactive processes between the particles play a crucial role in the ignition and combustion behavior and pollutant formation and destruction. Annamalai et al. studied isolated coal/char particles as an introductory material to interactive processes for solid particle arrays, streams, and clouds [46, 47]. The interactions occur through processes ranging from purely diffusive to convective transport processes. Although there is no systematic study for arrays of char or coal particles, they found that there is a strong analogy of the group ignition and combustion to porous char ignition and combustion. Interesting results for the ignition characteristics of coal dispersions are obtained, that the particles with relatively small or low volatile matter which ignite heterogeneously when isolated are found to ignite homogeneously under cloud conditions. The minimum ignition temperature is found to increase with a decrease in size under isolated mode while the opposite is true under interactions [46, 47]. Clouds of particles can represent either batch or continuous ignition, essentially depending on the relative scale of the cloud to the ignition source, and the phenomena may be less directly related to each other than is commonly assumed [15]. The interactive or cooperative influences between particles are hard to understand when comparing the fundamental research results to clouds ignition or real PC flames studies.

Third, most single coal particle ignition models do not take account of convection flux term, which may influence both mass transfer and heat transfer during the ignition. Katalambula showed that the amount of volatiles remaining in the vicinity of the particle
is significantly affected by natural and/or forced convection, which in turn affects the ignition mechanism and temperature. Under negligible and natural convections, coal ignited homogeneously, while under forced convection, it ignited heterogeneously. Ignition temperatures were highest when a particle was surrounded by the largest amount of volatiles and lowest when the volatile amount was the least. Further, the ignition temperature decreased with the volatile matter content of coal under negligible and natural convection. Under forced convection, however, the ignition temperature remained more or less constant [25].

Last, but maybe not the least, in real field boilers, with the mixing affect introduced by the large eddies in turbulence, single coal particle ignition mechanism must be coupled with turbulent mixing to understand or predict the ignition and the flame stability. Turbulence can easily wipe off the gradients of concentrations, temperatures, or velocities, which dramatically changes the simplicity of the single coal particle ignition mechanism. The gap between the fundamental research and the real industrial applications is still very large and will continue to remain a challenge to engineers and scientists.

### 1.3 Near-Burner Phenomena Studies

### 1.3.1 Challenges in Near-Burner Phenomena Studies

The near-burner region can be defined by Figure 2.

Measurements in industrial swirling flames of high and medium volatile bituminous coals show that NO\textsubscript{x} production and destruction can take place in a region close to the burner, as defined in Figure 2 [48, 49]. Char burnout as high as 80\% and NO\textsubscript{x}
concentrations representative of the flue gas concentrations levels are typically measured within two quarl diameter downstream of the burner outlet. The flow pattern in the quarl zone and consequent mixing determine the pollutant formation characteristics of swirl-stabilized flames. Unfortunately, there has seldom been much agreement between the simulation and the experimental data in the near-burner zone [17, 48, 50-66]. This may be due to various reasons [48, 52, 54, 57, 58]. One reason is that the detailed fluid dynamics and flame structure in the near-burner zone are very complex. Another reason for discrepancies between simulation and data may be due to the intrusive in-flame measurement techniques employed [57, 58]. Once a probe is inserted into the flame, it is difficult to quantify the disturbance introduced to the flame and the continuous reaction inside the probe. Nonintrusive optical diagnostics may be a good technique to quantify the flame without influencing it. Examples in the literature are by Olivani et al., who used PIV (Particle Image Velocimetry) and LDV (Laser Doppler Velocimetry) to obtain a
comprehensive analysis of the velocity field, and optical still photography for the
detection of flame front and main visible flames [53]. On the simulation side, the
accuracy of the model could not be definitively established due to a lack of detailed
measurements in the near-burner region of the combustor and an incomplete
understanding of the devolatilization and char combustion of the chosen coal [57].
Another example of the complexity in turbulent jets in the near-burner region is given by
Budilarto and Sinclair [50, 51], who suggested that the coal ignition submodel should
capture observations that smaller particles preferentially migrate to the jet edge due to
turbulent eddies, while larger particles keep travelling in the center of the coal jet due to
the inertia.

1.3.2 The Coaxial Jet

The coaxial jet, defined as a central round jet being surrounded by an annular jet,
is a common geometry for pulverized coal combustors, such as cement kilns and
tangentially fired boilers [35, 67]. Figure 3 shows a velocity profile at the nozzle exit of a
coaxial jet [50].

In the near field region of a coaxial jet, the annular and the central jets have not
fully merged. Fluid aerodynamics can be characterized by two important parameters, the
momentum flux ratio between the two jet streams, and the ratio of the annular and central
nozzle diameters [17, 50, 68]. The velocity ratio of the annular to central jet is also
applied to characterize the burner aerodynamics, especially when the fluid densities are
the same. The momentum flux ratio can be deduced to the corresponding velocity ratio
[50, 67, 68]. In a coaxial coal jet, fluid-particle interaction and particle motion, which are
relevant to the fluid aerodynamics in the near field region, are expected to be understood.
Budilarto summarized the research both on a single-phase coaxial jet and coaxial particle laden jet [50].

Rehab et al. (1997) investigated the near field vortex structure in a single-phase coaxial jet with a velocity ratio (annular to central jet inlet velocity) ranging between 2 and 15. They reported that the interaction between the two shear layers moved closer to the nozzle with increasing velocity ratio and the length of potential core was reduced with increasing velocity ratio. When the velocity ratio was greater than the critical value, the central potential core was truncated and is followed by an unsteady recirculation bubble, which has a wake-typed instability. The size of the recirculation bubble increased with increasing velocity ratio and reached a maximum length for a velocity ratio of infinity.
For a velocity ratio smaller than the critical value, the fast annular jet periodically pinched the central jet near the end of the central potential core [50].

Mostafa et al. (1990) studied the coaxial particle-laden jet and suggested that the mixing between the annular and central jet streams was responsible for the observed variation in mean particle velocity and particle number density profile with velocity ratio. Fan et al. (1996) investigated the effect of solid loading, particle size, and velocity ratio on the dispersion of particles and gas in the fully merged zone of a coaxial particle-laden jet. They found that the dispersion of the gas and particle was enhanced when the annular jet velocity was raised, while the central jet velocity was maintained at the same value (increasing velocity ratio). For the same solid loading, the radial distribution of particles for the case of larger velocity ratio was observed to be flatter than that for the case of smaller velocity ratio [50].

Budilarto studied the effect of velocity ratio on the motion of particles in coaxial particle-laden jets such as the radial dispersion of particles, and the effect of particle size distribution on the motion of particles in particle-laden flows loaded with binary mixtures of two different sized particles. His experimental study was undertaken to investigate the effect of fine particles on the motion of the coarser particles and vice versa. He reported that velocity ratio is one of the most important parameters controlling the flow aerodynamics in the near field region of a coaxial jet. It was observed that as the velocity ratio (annular to central jet inlet velocity) increases, the instantaneous particle structure tends to become wavier and more symmetric. The measurement found that the ratio of radial velocity to axial mean velocity, and the ratio of radial mean velocity to axial mean velocity are important parameters for characterizing the variation in the radial spreading and particle number density profile. The time averaged measurement of instantaneous
radial velocity is strongly related to the instantaneous structures of particles in coaxial particle-laden jets [50].

Budilarto also found that the presence of the finer particles tends to increase the drag force on the coarse particles as the gas-phase viscosity increases. Moreover, the presence of the fine particles also enhances the velocity fluctuation of the coarse particles. Increasing mass fraction of the finer particles in the mixture leads to a decrease in the radial mean velocity of the coarse particles [50].

The above review on the coaxial jet has not revealed the coupling effect between the turbulent mixing effect and the coal jet ignition mechanism. The actual problem of understanding coaxial coal jet flame is far more complicated than merely understanding the fluid aerodynamics. However, it is very important to understand the fact that in pulverized coal combustions, a variation in velocity ratio will lead to a variation in oxygen concentration in the near field region because velocity ratio controls the turbulent mixing process between the annular and central jet. The turbulent mixing was the slowest for velocity ratio of one because the shear stress caused by the velocity gradient between the two layers dominates the turbulent mixing. Moreover, particle dynamics in a pulverized coal combustor is much more complex than in an isothermal coaxial jet. For instance, the combustion reaction on a particle surface will induce a reduction in particle size and particle density and the changes in particle properties will affect the motion and trajectories of the coal particles [50, 51]. Therefore, challenges, such as understanding particle dynamics, turbulent mixing between the central and annular jet, reaction kinetics of combustion, the variation in particle properties due to the combustion reaction, and the effect of temperature variation due to heat transfer and reactions on fluid aerodynamics, have always been the world-wide research interests.
The above literature review also helps with the burner design in Chapter 3, which is going to be discussed later.

1.3.3 Flame Stability

In a practical device, a stable flame is one that is anchored at a desired location and is resistant to flashback, liftoff (also called standoff), and blowoff over the device operating range [49]. At sufficiently low flow rates, the base of a jet flame lies quite close to the burner tube outlet and is said to be attached. As the fuel flow rate is increased, inconsistent structures begin to form in the flame sheet at the base of the flame, and with further increase in the flow rate, more and more holes form until there is no continuous flame close to the burner port. This condition is called liftoff. With yet further increases in flow rate, the liftoff distance (the distance from the burner port to the flame base) increases. At a sufficiently large flow rate, the flame blows out. Thus, there are two critical flow conditions related to flame stability, liftoff, and blowout. Pitts summarized the three different theories proposed to explain liftoff [49]:

Theory I: The local flow velocity at the position where the laminar flame speed is a maximum matches the turbulent burning velocity of a premixed flame.

Theory II: The local strain rates in the fluid exceed the extinction strain rate for a laminar diffusion flamelet.

Theory III: The time available for backmixing by large-scale flow structures of hot products with fresh mixture is less than a critical chemical time required for ignition.

In general, the criteria of establishing a stable turbulent flame are:

1) the local flow velocity is lower than the turbulent flame speed;

2) the reacting mixture is within the flammability limits.
Flame stability is a very important issue for the burner design. Lift off should be avoided so that the flame is close to the burner and its position is independent of the flowrate [49]. Flame stability also affects heat transfer profile inside the utility boiler and pollutant emissions such as NO₃ [48, 49]. Therefore, understanding flame stability has very practical meanings and applications.

Flame stability is often quantified as a function of many parameters, such as swirl number, stoichiometry, coal loading, temperature, and coal type [25, 48, 52, 54, 69, 70]. Flame stability can also be described by the attachment or detachment of the flames in the experiments. Standoff distance (also called lift off distance) is a parameter used to describe the flame stability. When standoff distance is zero, the flame is attached and stable. For unstable detached flames, standoff distance is usually defined in the experiments as the distance from the burner tip to the base of the flame. However, Truelove et al. suggested the flame standoff is taken as the distance at which 3% of the coal mass is devolatilized for prediction purposes [54]. Essenhigh etc. used 1% burnout as an arbitrary measure of ignition [15]. The stability limits of a nonpremixed burner arrangement are quantified as a function of swirl number, quarl length, burner confinement, and mixtures of pulverized solid fuel and natural gas. Most scientists focus on the above parameters which influence the flame stability [20, 25, 44, 48, 54, 69-75]. But few studies considered the effect of oxygen partial pressure, which becomes another degree of freedom in oxy-coal combustion. Axelbaum’s group at Washington University [73] reported that an increase in O₂ concentration improves flame stability while replacing N₂ with CO₂ results in reduced flame stability. They characterized flame stability by the primary oxidizer Reynolds number at flame blowoff (Type I PC flames) and this methodology applied is similar to Anderson’s [71]. Axelbaum et al. found the
air-fired flame and the 30% O₂/70% CO₂ flame have similar blow-off velocity limits. The flame with 6% O₂ in the primary oxidizer and 35% O₂ in the secondary oxidizer also has comparable blow-off velocity limits; suggesting the potential for reduced NOₓ due to the removal of O₂ from the high temperature region of the flame without sacrificing flame stability [73]. However, standoff distance, as a direct parameter to quantify flame stability for the convenience of burner design, may be greatly influenced by the oxygen partial pressure in oxy-coal combustion. This has become an urgent research interest due to the fact that corresponding research is still inadequate.

### 1.4 Pollutant Reduction during Oxy-coal Combustion

The reduction of SOₓ and NOₓ in oxy-coal combustion has been reported by many scientists [74, 76-94], whose studies were completed either in lab scale or pilot scale furnaces.

Because N₂ is absent under oxy-coal combustion conditions, theoretically, there is no thermal NOₓ formation while fuel NOₓ is dominant. Liu and Okazaki [85-87, 89] reported that the conversion ratio from fuel-N to exhaust NO was automatically reduced to less than about one fourth of conventional PC firing, mainly due to the reduction (or reburning) of recycled NO in the combustion zone. These detailed mechanisms were also discussed by Okazaki and Ando [89]. Ogden and Wendt studied the flame attachment and NOₓ emissions using oxygen enrichment for Type 0 PC flame [74, 88]. Liu et al. found air/oxidant staging is a very effective method in reducing NOₓ emissions for both coal combustion in air and coal combustion in 30% O₂/70% CO₂ [86]. Croiset and Thambimuthu from CANMET compared the coal combustion in once-through O₂/CO₂ mixtures and experiments with recycled flue gas [78]. They found that combustion with
recycled flue gas leads to lower NOx emission rate than for once-through combustion in O2/CO2 mixtures, which also agreed with the results of Okazaki and Nozaki et al. [89, 95]. Hu and Kobayashi et al. discussed the effect of temperature on NOx emissions in the presence of recycled flue gas [80]. Increasing the temperature in the presence of excess oxidants will accelerate the oxidation of fuel nitrogen components to NO; on the other hand, at higher temperatures, volatiles are predicted to be more rapidly evolved and hence will have a higher average concentration in the early stage of combustion, resulting in fuel rich zones for enhanced NO reduction to N2. NO reduction by char is also enhanced at higher temperature due to the increased rates of reaction, although it provides only a marginal contribution to the total NO reduction. Therefore, the net results depend on the combustion conditions and the coal type [80].

1.5 Summary of Literature Review

1) Coal particle ignition mechanisms under air-fired condition have been well investigated. However in oxy-coal combustion conditions, the corresponding experimental data and theoretical mechanism are still missing. Although single particle data suggest that differences in O2 transport rates to the particle surface play a role, effects of the replacement of N2 by CO2 are not understood.

2) Pollutant formation, such as NOx and SOx emissions, is being widely investigated both experimentally and theoretically. The fuel NOx mechanism for oxy-coal combustion is relatively well understood.

3) Due to various reasons, there is usually poor agreement between experimental results and simulations in the near burner zone. In-flame measurements in the near burner
zone are extremely difficult. Corresponding experimental data are still inadequate for simulation validation.

4) The partial pressure of oxygen is another degree of freedom in oxy-coal combustion and can influence the flame stability, but few studies have been completed. Additional systematic studies are required to quantify this effect.
2. SCOPE OF THIS WORK

2.1 Motivation

Oxy-coal combustion introduces an additional variable to those present in air-fired configurations, namely the concentration of O$_2$ in the inlet oxidant mixture [2]. In practical turbulent diffusion flames, the overall inlet oxidant stream is split into at least two streams: a primary stream that transports the pulverized coal to and through the coal injector within the burner, and a secondary stream that mixes with the primary coal jet downstream of the burner. In contrast to air combustion, the amount of oxygen within the primary jet in oxy-coal combustion is a variable which can be set anywhere from zero (or to the exhaust % O$_2$) up to any value that is considered safe. There are incentives from a safety point of view to minimize the number of places in which fresh, pure oxygen must be introduced [57]. For retrofit purposes, it is desirable to understand how replacement of N$_2$ by CO$_2$ will affect flame stability [2, 96] and flame standoff distance, and to predict the results.

To this end, the research described here focuses on interactions between known coal ignition chemistry mechanisms [15-34, 37, 41-43, 46, 47, 67, 83, 92, 97, 98] and known turbulent two-phase jet flow characteristics [17, 50-54, 58, 59, 62, 64], and attempts to weave connections between the two. Rather than providing either new fundamental data or new field test data, this research is designed to provide a “bridge” between the laminar flame reactor results of others [17, 20, 28, 31, 32, 41, 46, 47, 99],
and their application to practical burner configurations in the field [2, 5-10, 17, 81, 92, 100]. This “bridge” takes the form of a well-defined 40kW prototype coaxial turbulent diffusion oxy-coal flame, supported in a test rig that was rated up to 100kW. This system is small enough to allow targeted experiments using systematic variation of momenta, velocities, and gas stream compositions, but large enough to contain the essential physics of larger scale pilot rigs and field units.

While it is known that decreasing the oxygen content of an O\textsubscript{2}/N\textsubscript{2} primary stream can lead to flame instabilities and flame detachment [2, 28, 31, 45, 81, 96, 101], the effects of O\textsubscript{2} concentration in O\textsubscript{2}/CO\textsubscript{2} primary streams have hitherto not been investigated. The Sandia group led by Shaddix has shown that differences between air- and oxy-fired coal particle ignition times and char burnout times can be attributed to differences in molecular diffusion rates of O\textsubscript{2} in N\textsubscript{2} and CO\textsubscript{2} [28, 31, 45]. B&W research group found that devolatilization under a CO\textsubscript{2} atmosphere is greatly affected by the CO\textsubscript{2} gasification reaction, and reduced oxygen diffusion to the particle surface in CO\textsubscript{2} is also important under oxy-combustion condition [33, 97]. The Sinclair-Curtis group at Purdue has shown that in two-phase turbulent axial jets, small particles are preferentially transported to the outside boundaries of the jet, where ignition might be more likely [50, 51].

In this work, we attempt to relate these types of fundamental observations to practical Type 0, coaxial turbulent diffusion flames (shown in Figure 4) that are representative of flames in tangentially fired boilers and cement kilns. Furthermore, although the well-defined coaxial flame type under consideration here was chosen because of its simplicity and suitability for simulation, it does have direct practical relevance to certain industrial oxy-coal combustion configurations, such as tangentially
Figure 4. Type 0 flame: picture on the left shows attached and detached Type 0 flames; picture on the right shows a typical Type 0 attached oxy-coal flame (shutter speed 0.25 ms)

fired boilers and cement kilns. Therefore, this work comprises the first steps towards understanding the stability of turbulent oxy-coal flames in general.

2.2 Objectives and Scope

The specific objectives of the research presented here are:

1) to quantify effects of oxygen concentration in the primary O₂/CO₂ stream on flame standoff distance in well-defined coaxial, turbulent oxy-coal diffusion flames;

2) to understand the interactions between known coal ignition mechanisms and turbulent, two-phase, jet flow fields;

3) to contribute to the validation, with error quantification, of future simulations of this prototype integrated oxy-coal combustion experiment. These simulations would be
designed to predict effects of oxy-coal retrofit on flame stability in practical coal combustion configurations.

The remainder of this dissertation consists of the following parts. In Chapter 3, the experimental setup of the oxy-fuel combustor (OFC), designed and constructed as part of this work, is described in detail, together with the design rationale involved. The research focus is on quantifying flame stability of coaxial pulverized coal turbulent diffusion flames. No generally accepted method of accomplishing this currently exists. Therefore, Chapter 4 describes how we developed a methodology that allowed quantification of flame stability. Chapter 4 also includes a brief introduction of the definition of flame stability, the standoff distance in this work, and the statistical approach applied to quantify the flame stability. Chapter 5 then presents the results of preliminary tests to validate the methodology. Then, Chapter 6 shows the results of the effect of different burner operating parameters, especially partial pressure of oxygen, on flame stability. Chapter 7 discusses the underlying mechanism which affects flame stability and tries to wave connections between fundamental observations and practical Type 0, coaxial turbulent diffusion flames that are representative in tangentially fired boilers and cement kilns. Finally, this dissertation is wrapped up by conclusions and future work suggestions, which are Chapter 8 and Chapter 9, respectively.
3. EXPERIMENTAL SETUP

A new 100 kW (nominal) down-fired, oxy-coal combustion furnace (OFC) was designed and constructed to allow for the systematic investigation of near-burner aerodynamics of axial diffusion flames using a mixture of oxygen/carbon dioxide to replace the combustion air [102, 103]. It has heated walls and quartz windows for optical access that permit flame detachment studies and future optical diagnostics. The new furnace will simulate the environments experienced by PC jet flames in certain boilers (such as tangentially fired units) and will provide for the systematic control of burner momentum and velocity variables, as well as wall temperatures. The furnace consists of an oxy-fuel combustion chamber, followed by a downstream section with controlled temperature cooling to simulate practical furnace conditions. It allows stabilization of axial Type 0 (no swirl) PC diffusion flames, through the use of heated walls, and variations of oxygen content of transport and secondary air streams. It also represents those typical of existing tangentially fired boilers or cement kilns. The time-temperature history for combustion with air represents that of existing boilers.

This chapter describes the details of design and construction of the OFC furnace, with troubleshooting and facility shake-down processes. One of the key factors, steady coal feeding, is critical to the data quality in this research. The tremendous efforts of improving coal feeding behavior are also explained. The burner design information can
also be found in this chapter. The safety operation procedures can be found in Appendix E.

3.1 Reactor Design Criteria

1) The designed coal firing rate is 100 kW, which is large enough to meet the requirements of laboratory scale tests, but small enough to maintain the flexibility of the operations and the budget.

2) It has systematic control of burner operating parameters and can allow systematic studies on the effects of various operating parameters, such as inlet gas concentrations, inlet gas flowing rates, coal feeding rates, wall temperatures, inlet gas stream temperatures, and pressures, etc.

3) It allows accurate and instantaneous control and measurements of combustion parameters.

4) It has an automatic and intelligent control and data acquisition system, together with safety features for emergency situations.

5) It has reliability for long-time operating condition with minimal maintenance.

6) The temperature history design is based on Figure 5.

Furnace operation and control methodology must focus on the near-burner region and wall effects. The potential impingement of the flame jets on the furnace walls should be minimized [74]. The jet usually exerts a 9-10° angle of divergence [35, 104, 105]. Ogden suggested using a 30:1 ratio of furnace to inner jet diameter as the criterion to determine the minimum furnace diameter to prevent wall impingement[74]. In our case, this ratio is around 39, which is large enough to eliminate the wall impingement.
3.2 Furnace Pictures and Design Schematics

Figure 6 shows the schematic of our oxy-fuel combustion (OFC) experimental apparatus. The upper right corner shows one of the coaxial coal burners applied in this study.

Another picture of the furnace is shown in Figure 7.

Figure 8 shows the P&ID flow chart of the OFC system.

From the top section to the bottom one, and then to the last section connecting the stack, nine sections are named in turn. During the design, this furnace is divided into three zones, as shown in Figure 6:

1) the burner zone (the top section, section 1);
2) the radiant zone (the vertical sections excluding the top section, section 2 - 5);
Figure 6. OFC Experimental apparatus and coaxial burner schematic.
Figure 7. A picture of University of Utah OFC furnace
Figure 8. P&ID flow of the OFC system
3) the convective zone (the horizontal sections, section 6 - 9).

The design and construction details of the above three zones are going to be provided in Section 3.3 – 3.5.

### 3.3 Burner Zone

The top section (as shown in Figure 9 and Figure 10) is the burner zone, with dimensions of 0.610 m I.D., 0.914 m O.D., and 1.219 m in height. It is insulated by 2600 Fiberboard (temperature tolerance limit: 2600 °F) with a thickness of 76 mm. The burner zone is heated electrically by 24, 840 W flanged ceramic plate heaters (3 rows and 8 heaters per row, as shown in Figure 10). This enables the 100 kW system to simulate larger boilers in the field. Each row of heaters is embedded with K-type thermocouples (Omega) to control or monitor the temperature independently. The independent control of wall temperature provides another degree of freedom, which may impact PC ignition or flame attachment/detachment during the combustion process.

The wall heaters (FPH204, Thercraft), 6” wide by 10” tall, are mounted to the interior furnace walls by titanium brackets. The embedded heating elements can operate continuously under oxidizing conditions at temperatures up to 1370 K (1100 °C). The temperature of the wall heaters is controlled and monitored by Opto22 software, which is going to be discussed later. K-thermal couples are installed to measure the temperature of the heaters on the back without being exposed to the hot combustion gas. The Fibercraft ceramic plate heater properties are listed in Table 1.

Figure 9 also shows the optical window blocks, which are for the optical measurement and the future laser diagnostics. There are four optical window blocks facing in the opposite way, as shown in Figure 9 (in a top view of the top section, the
Figure 9. Design sketch of the top section

Figure 10. View of inside of top section chamber, showing electric heaters and view of optical windows
Table 1. Fibercraft properties

<table>
<thead>
<tr>
<th>Property</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Composition (Al₂O₃/SiO₂)</td>
<td>38%/60%</td>
</tr>
<tr>
<td>Thermal Conductivity at 1100 °C</td>
<td>0.22 W/M-K</td>
</tr>
<tr>
<td>Flexural Strength</td>
<td>0.17 MPa</td>
</tr>
<tr>
<td>Board Thickness</td>
<td>1” and 2”</td>
</tr>
</tbody>
</table>

distribution pattern is every 90° per window block). There are three circular flanges shown in Figure 9. In reality, they are used for installing K-type thermocouples to measure the gas temperature near the wall inside the chamber (shown in Figure 11 and Figure 12). There are another three circular flanges on the other side of the top section, which are used to install quartz discs to view flames from different locations.

The optical window is made of three 3” wide by 12” long quartz windows (thickness: 5 mm). A 3” wide by 44” long quartz window was initially proposed for the optical measurements, but it broke early in the program due to the destructive thermal stress during the furnace shutdown. Therefore, later we designed the three-quartz-window pattern, which can better handle the thermal stress and can last longer. Another important concern is how to keep the window clean with ash accumulating during the experiment. This issue has been discussed by Ranner et al. in 2007 [106]. In this experiment, a simple yet effective method is applied to keep the quartz windows clean. A ¾” nipple with a cap was installed on top of the quartz window frame. A purging tube can be carefully inserted with the purging gas (CO₂ or air) blowing off the ash fouling every 30 minutes. The gasket material is 1” thick Fiberwool insulation paper, which has proven to be the best choice so far in more than two years of tests.
Figure 11. A picture of the top section of OFC furnace with a light blue natural gas flame.

Figure 12. A picture of the top section of OFC furnace with a PC flame fired.
3.4 Radiant Zone

Three layers of insulation are installed in the radiant zone: 1900 Fiberboard (thickness: 51 mm), 2600 Fiberboard (thickness: 76 mm), and 700 Ultra Green Refractory. B-type (Pt-Rd) thermocouples with ceramic shell surrounding the tip are installed in the flanges of this zone according to the temperature history profile shown in Figure 5. However, it is suggested that in the future, those B thermocouples should be replaced by K thermocouple to gain a quicker response and more accurate temperature measurements.

One of the two flanges of section 5 is applied for extractive sampling for aerosol measurements, such as Loss-On-Ignition (LOI), Scanning Mobility Particle Sizer (SMPS), Low-Pressure-Impactor (LPI), etc.[99].

An ash port is located in the bottom of section 5, as shown in Figure 6 and Figure 7. Ash is usually collected during maintenance through this port.

3.5 Convective Zone

Two layers of insulation are installed in the convective zone: 2600 fiberboard (thickness: 76 mm), and 700 ultra green castable refractory (thickness: 51 mm). Eight heat exchangers in the convection section, which allow the simulation of super heaters in an industrial boiler, cool the flue gas before entering the exhaust system. A probe is inserted into section 9, the last section, to measure the gas species, such as O₂, CO₂, CO, NOₓ, and SOₓ, etc.
3.6 Pressure Control System

A pressure transmitter is installed in section 3 to monitor the internal pressure of the furnace. The combustion exhausts leave the convection zone and enter the stack, which is a 9” I.D. pipe connected to the main exhaust pipe of the lab. An induced draft fan provides the necessary suction to draw the flue gases out of the furnace. A damper is installed in the 9” exhaust pipe to help control the furnace pressure by adjusting its opening. An ash discharger is installed underneath the damper to collect the ash, as shown in Figure 6. There are a series of dampers installed in the lab along the exhaust line. All of them can help to adjust the pressure if needed. No emission control device is installed in the lab at this point in time.

3.7 Gas Delivery System

The air is delivered by a 25 horsepower Sullair compressor which provides 120 psi compressed air through the workshop. The primary air flowing rate is controlled by a mass flow controller shared with the primary CO$_2$ line. The secondary air flowing rate is controlled by a P-dP v-cone shared with secondary CO$_2$ line. A typical air-firing Utah Bituminous coal flame case is the following: coal feeding rate as 4.84 kg/hr (10.67 lb/hr), overall stoichiometric ratio (S.R.) as 1.15, primary air flowing rate as 4.63 kg/hr (10.2 lb/hr), and secondary air flowing rate as 43.1 kg/hr (95 lb/hr).

Both CO$_2$ and O$_2$ are supplied from tanks constructed and supported by Praxair Inc. The purpose of building two tanks (O$_2$ and CO$_2$) is to provide a once-through O$_2$/CO$_2$ mixture for the OFC system. Figure 13 and Figure 14 show the O$_2$ tank and CO$_2$ tank constructed, respectively, with the help of Praxair Inc. As shown in Figure 13, a large vaporizer was constructed to vaporize the liquid oxygen. Over two years of effort and
many hours of professional staff time were required in accomplishing this phase of research.

It is very important to note that constructing the O\textsubscript{2} line requires that the certified professional crew follows certified procedures and uses certified parts. When operating the combustion system with pure O\textsubscript{2} introduced, it is very important to make sure the background gas (such as air or CO\textsubscript{2}) flow has been steadily established, especially in the primary stream line. Caution should be taken to avoid potential accidents.
3.8 Steady Coal Feeding

The establishment of steady coal feeding was one of the biggest challenges in this research. Coal feeding is a critical factor in obtaining quality data.

Unsteady feeding can cause the following problems:

1) Nonuniform and noncontinuous coal feeding.

2) A heavily fluctuating flame, instead of a stable turbulent coal flame.

3) A bad mass balance when monitoring the major species of the exhaust and a higher percentage of unburned carbon in the ash.

4) A large systematic error when performing flame stability studies.

To ensure a steady PC feeding, numerous technical details are summarized here:

1) Any large pressure drop in the line of primary coal jet and downstream of coal feeder should be avoided.

2) Vibration of eductor can help improve the coal feeding. However, it is not viable when the eductor is attached to a loss-in-weight coal feeder because vibration is
harmful to the loss-in-weight function, which monitors the mass loss on the scale and adjusts the feeding instantaneously and automatically.

3) The selection of the coal feeder should match its optimum working range. A PC feeder works best at 40% to 60% of the motor’s range. In general, 1000 rpm is the best choice for uniform feeding. Higher rpm’s can cause PC stick in the feeder outlet; therefore, 1000 rpm is the optimal for motor speed.

4) A twin-screw loss-in-weight feeder (as shown in Figure 15) works better than a single-screw non-loss-in-weight feeder.

5) An agitator installed in the hopper can prevent bridging when feeding coal.

6) An optimized design of an eductor can break the coal clumps at the exit of screws.

Figure 15. K-Tron loss-in-weight twin-screw coal feeder applied in oxy-coal combustion lab, University of Utah
The unique design of the eductor includes the following features:

1) A purging loop (also called high velocity mixing loop) was installed, as shown in Figure 16. This design can introduce a local high velocity swirl inside the eductor, removing PC from the augers at the exit.

2) A mesh was set up in the exit of the twin screws, as shown in Figure 17. The mesh can break up the PC clumps in the feeder exit, which significantly improves the feeding and reduces pulsing.

Five methods have been used to verify the steady feeding behavior:

1) The coal jet and the flame were visually inspected to ensure the steady feeding during the test.

2) A total of 500 continuous pictures was collected by the Epix CMOS camera (SV5C10) in approximately 20 seconds using a frequency of 24 fps (frames per second). Although a fluctuating nature of the flame is observed in the pictures, a relatively steady flame shape was also captured in each picture, indicating steady feeding behavior.

3) O₂, CO₂, and NOₓ exhaust levels were all monitored during the test and a mass balance was obtained. The O₂ level matched the results of theoretical calculations and was always steady under different running conditions.

4) Loss-on-ignition (LOI) ash samples were collected during the combustion, and a high conversion rate of the carbon was always observed, which shows full combustion of coal particles and a steady feeding process.

5) A Photron high speed camera was applied at 5000 fps and 1/200 ms shutter speed to check the feeding behavior. In the steady feeding process, the measured temporal variations had a much higher frequency than the frequency caused by auger rotation (0.73 Hz).
Figure 16. An eductor design schematic in oxy-coal combustion lab, University of Utah
3.9 Intelligent Control – Opto22

The test facility has a modern digital control system (Opto22) with a graphical user interface, which can automatically control the furnace and continuously acquire data during the test. The data, including measurements of temperature, pressure, and gas components, etc., can also be acquired by the Opto22 instantaneously and automatically. Safety features prevent accidents or unnecessary damage. Figure 18 shows the control box where Opto22 modules and other automatic control modules are installed. Figure 19 shows the interface of the Opto22 Software.

3.10 Gas Analyzers

Gas species in the exhaust are monitored by two sets of gas analyzers:

- O₂: Yokogawa - Zirconia oxygen analyzer ZA8 (Qty: 1), Horiba - Paramagnetic oxygen analyzer (Qty: 1)
- CO₂: California Analytical Instrument - Infrared gas analyzer: ZRH(Qty: 2), and ZRE (Qty: 1)
- NOₓ: Thermal Environmental Instrument – Chemiluminescence NOx analyzer (Qty: 1), Horiba - Chemiluminescence NOx analyzer CLA-510SS (Qty: 1)

The global mass balance was validated by measuring the major species of the combustion product in the exhaust. The sampling probe was inserted into the end of section 9, right before the exhaust enters the stack. The exhaust was also quenched by a refrigerator before entering the gas analyzers. The discussion of oxy-coal combustion confines on chemiluminescence NOₓ measurement can be found in Appendix A.
Figure 17. A mesh installed inside the eductor at the exit of feeder screws

Figure 18. Opto22 Control box
Figure 19. An Opto22 commercial software interface to control our oxy-coal combustor and to acquire data
3.11 Coal Samples

The major coal specie employed in this study is Utah Bituminous pulverized coal. The mass average size of the particles is about 50 micron. Another type of coal, Power River Basin (PRB) coal is also tested. The coal analysis is shown in Table 2. The particle size distributions of Utah Bituminous coal and PRB coal are shown in Table 3 and Table 4, respectively.

Table 2. Coal analysis: Utah Bituminous coal and PRB coal.

<table>
<thead>
<tr>
<th>Coal Analysis</th>
<th>Ultimate (wt%, daf)</th>
<th>Proximate (wt%)</th>
<th>Higher (gross) heating value (HHV)</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>C</td>
<td>Moisture</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Utah Bituminous</td>
<td>77.75</td>
<td>3.03</td>
<td>27,286 kJ/kg</td>
<td></td>
</tr>
<tr>
<td>PRB</td>
<td>68.40</td>
<td>21.30</td>
<td>21,627 kJ/kg</td>
<td></td>
</tr>
</tbody>
</table>

Table 3. Utah Bituminous coal particle size distribution.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Size (micron)</th>
<th>Percent</th>
<th>Cumulative</th>
<th>Passed through</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.0%</td>
<td>0.0%</td>
<td>100.0%</td>
</tr>
<tr>
<td>80</td>
<td>178</td>
<td>1.2%</td>
<td>1.2%</td>
<td>98.8%</td>
</tr>
<tr>
<td>100</td>
<td>152</td>
<td>2.5%</td>
<td>3.7%</td>
<td>96.3%</td>
</tr>
<tr>
<td>150</td>
<td>106</td>
<td>13.8%</td>
<td>17.5%</td>
<td>82.5%</td>
</tr>
<tr>
<td>200</td>
<td>75</td>
<td>12.7%</td>
<td>30.3%</td>
<td>69.8%</td>
</tr>
<tr>
<td>250</td>
<td>63</td>
<td>58.6%</td>
<td>88.8%</td>
<td>11.2%</td>
</tr>
<tr>
<td>325</td>
<td>44</td>
<td>5.3%</td>
<td>94.1%</td>
<td>5.9%</td>
</tr>
<tr>
<td>400</td>
<td>37</td>
<td>5.9%</td>
<td>100.0%</td>
<td>0.0%</td>
</tr>
</tbody>
</table>
Table 4. PRB coal particle size distribution.

<table>
<thead>
<tr>
<th>Mesh</th>
<th>Size (micron)</th>
<th>Percent</th>
<th>Cumulative</th>
<th>passed through</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
<td>0.0%</td>
<td>0.0%</td>
<td>100%</td>
</tr>
<tr>
<td>100</td>
<td>152</td>
<td>7.0%</td>
<td>7.0%</td>
<td>93.0%</td>
</tr>
<tr>
<td>150</td>
<td>106</td>
<td>9.2%</td>
<td>16.2%</td>
<td>83.8%</td>
</tr>
<tr>
<td>200</td>
<td>75</td>
<td>13.7%</td>
<td>29.9%</td>
<td>70.1%</td>
</tr>
<tr>
<td>270</td>
<td>53</td>
<td>13.7%</td>
<td>43.6%</td>
<td>56.4%</td>
</tr>
<tr>
<td>325</td>
<td>44</td>
<td>9.8%</td>
<td>53.4%</td>
<td>46.6%</td>
</tr>
<tr>
<td>400</td>
<td>37</td>
<td>2.7%</td>
<td>56.1%</td>
<td>43.9%</td>
</tr>
<tr>
<td>&lt;37</td>
<td></td>
<td>43.9%</td>
<td>100%</td>
<td>0</td>
</tr>
</tbody>
</table>

3.12 Furnace Shakedown

The objective of the preliminary screening tests is to validate the equipment and operating envelope, including burner design, under air-firing or oxygen-enhanced conditions.

The new oxy-coal combustor was characterized by gas combustion initially. Figure 20 shows a natural gas flame. Characteristic times for the reactor to reach steady state (as shown in Table 5), temperature profiles (as shown in Table 6 and Table 7), and measured exhaust components, including NOx (as shown in Table 8 and Table 9), have been obtained for various natural gas combustion conditions. These results can help to understand the characteristics of the reactor. The effect of variations in the wall temperature was also investigated (as shown in Table 6). Wall temperatures can be adjusted as an independent variable, using the electric heaters in the burner chamber wall, and comprise another degree of freedom for controlling the jet ignition process in the combustor. The results shown in Table 5 suggest that the design was successful, and the furnace materials performed well, such that unsteady thermal behavior did not last for unreasonably long times.
Figure 20. A natural gas flame applied to characterize the combustor

Table 5. Time required to reach steady state under different natural gas firing rates.

<table>
<thead>
<tr>
<th>Depart from</th>
<th>Destination</th>
<th>Time needed (hours)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Room temperature              16.1 kW, SR=1.50</td>
<td>12</td>
<td></td>
</tr>
<tr>
<td>16.1 kW, SR=1.50              16.1 kW, SR=1.15</td>
<td>1</td>
<td></td>
</tr>
<tr>
<td>Flame off, T = 783 K           29.9 kW, SR=1.50</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>29.9 kW, SR=1.50              29.9 kW, SR=1.15</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>29.9 kW, SR=1.15              38.4 kW, SR=1.47</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>38.4 kW, SR=1.47              38.4 kW, SR=1.15</td>
<td>2</td>
<td></td>
</tr>
<tr>
<td>38.4 kW, SR=1.15              31.4 kW, SR=1.50</td>
<td>5</td>
<td></td>
</tr>
<tr>
<td>31.4 kW, SR=1.50              16.1 kW, SR=1.50</td>
<td>6</td>
<td></td>
</tr>
</tbody>
</table>

Table 6. Typical wall and gas temperatures at different firing rates.

<table>
<thead>
<tr>
<th>Firing rate (kW)</th>
<th>S.R.</th>
<th>Gas Temperature (K)</th>
<th>Wall Temperature (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>Top</td>
<td>middle</td>
</tr>
<tr>
<td>17.0</td>
<td>1.15</td>
<td>1001</td>
<td>1004</td>
</tr>
<tr>
<td>31.7</td>
<td>1.15</td>
<td>1170</td>
<td>1179</td>
</tr>
<tr>
<td>41.3</td>
<td>1.13</td>
<td>1231</td>
<td>1240</td>
</tr>
<tr>
<td>17.6</td>
<td>1.50</td>
<td>963</td>
<td>964</td>
</tr>
<tr>
<td>31.7</td>
<td>1.50</td>
<td>1118</td>
<td>1125</td>
</tr>
<tr>
<td>33.1</td>
<td>1.50</td>
<td>1129</td>
<td>1136</td>
</tr>
<tr>
<td>41.6</td>
<td>1.72</td>
<td>1139</td>
<td>1145</td>
</tr>
<tr>
<td>31.7</td>
<td>0.89</td>
<td>1186</td>
<td>1195</td>
</tr>
</tbody>
</table>
Table 7. Effect of wall heating on measured gas and wall temperatures at a firing rate of 40.2 kW, and S.R. =1.15.

<table>
<thead>
<tr>
<th>Conditions</th>
<th>Gas Temperatures (K)</th>
<th>Wall Temperatures (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>top</td>
<td>middle</td>
</tr>
<tr>
<td>Without wall heated</td>
<td>1263</td>
<td>1274</td>
</tr>
<tr>
<td>Wall heated to 1200 K</td>
<td>1293</td>
<td>1306</td>
</tr>
<tr>
<td>Wall heated to 1228 K</td>
<td>1304</td>
<td>1318</td>
</tr>
<tr>
<td>Wall heated to 1255 K</td>
<td>1324</td>
<td>1337</td>
</tr>
<tr>
<td>Wall heated to 1283 K</td>
<td>1345</td>
<td>1357</td>
</tr>
<tr>
<td>Wall heated to 1311 K</td>
<td>1365</td>
<td>1376</td>
</tr>
</tbody>
</table>

Table 8. Exhaust components measured in the end of convection zone when burning natural gas.

<table>
<thead>
<tr>
<th>Components</th>
<th>16.1 kW SR = 1.11</th>
<th>39.3 kW SR = 1.13</th>
<th>29.5 kW SR = 1.17</th>
<th>31.4 kW SR = 1.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2 (v%)</td>
<td>2.8</td>
<td>2.8</td>
<td>3.6</td>
<td>8.7</td>
</tr>
<tr>
<td>CO2 (v%)</td>
<td>9.8</td>
<td>9.9</td>
<td>9.4</td>
<td>6.5</td>
</tr>
<tr>
<td>CO (ppm)</td>
<td>7</td>
<td>1</td>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>NO (ppm)</td>
<td>65</td>
<td>71.7</td>
<td>70.4</td>
<td>43.8</td>
</tr>
</tbody>
</table>

Table 9. Calculated (from mass balance) values of O2 and CO2 when burning natural gas.

<table>
<thead>
<tr>
<th>Components</th>
<th>SR = 1.11</th>
<th>SR = 1.13</th>
<th>SR = 1.15</th>
<th>SR = 1.17</th>
<th>SR = 1.50</th>
</tr>
</thead>
<tbody>
<tr>
<td>O2 (v%)</td>
<td>2.28</td>
<td>2.64</td>
<td>2.99</td>
<td>3.32</td>
<td>7.47</td>
</tr>
<tr>
<td>CO2 (v%)</td>
<td>10.59</td>
<td>10.39</td>
<td>10.19</td>
<td>10.00</td>
<td>7.64</td>
</tr>
</tbody>
</table>

Table 6 shows how wall and gas temperatures, with heaters off, depend on firing rate. Top, mid and bottom refer to 16.5 cm, 57.2 cm, and 97.8 cm away from the burner face in the axial direction, respectively. They all represent the gas temperatures close to the wall. Table 7 shows effects of external heating at the furnace walls on the measured wall temperatures and measured gas temperatures, at a firing rate of 40.2 kW and a stoichiometric ratio (SR) of 1.15.

Table 8 shows exhaust gas measurements at the end of the convection zone when burning natural gas. NO emissions are similar to what might be expected for unpreheated gas flames and consist of only thermal NO (from N2 fixation). Table 9 shows calculated
O\textsubscript{2} and CO\textsubscript{2} values for the same conditions measured and reported in Table 8. The comparison suggests that there may be a very slight leak of air either into the system, or into the sampling line, due to the slightly negative operating pressure of the reactor.

These natural gas tests showed that data gleaned from this furnace had good reproducibility. The system reached a steady thermal state fairly rapidly, and the allowable load that kept wall temperatures below the electric heater danger point was determined. The reactor is well designed and well built. It is also well insulated to prevent heat loss and well sealed to prevent leaking.

The next step in the preliminary tests involved firing PC with air or oxygen enhanced air. Temperature profiles, exhaust components, and flame standoff distances were measured during the tests. According to the temperature history, coal firing rate started at 4.3 lb/hr (1.95 kg/hr) in order to protect wall heaters. Wall temperature plays an important role in PC ignition. Moreover, increasing wall temperatures also helps with the flame attachment. For the conditions of 1.95 kg/hr coal feeding rate, S.R. of 1.15, and wall temperatures fixed at 1366 K, the corresponding gas temperatures are (from top to bottom at the same locations as noted in Table 3) 1393 K, 1400 K, and 1405 K. The typical exhaust components (at air-fired condition) measured are O\textsubscript{2}: 2.88 vol\%, CO\textsubscript{2}: 15.97 vol\%, CO: 17 ppm, NO: 363 ppm, and NO\textsubscript{2}: 21 ppm. Comparing with the calculated results for exhaust components based on measured feed rates (O\textsubscript{2}: 2.78 vol\%, CO\textsubscript{2}: 16.27 vol\%), the mass balance is enclosed.

During the tests, gas species in the exhaust are monitored to ensure the mass balance of the reaction. NO\textsubscript{x}, as an indicator of flame attachment or mixing process, is measured to help monitor the stability of the flame. For instance, Figure 21 shows how
NO$_x$ concentration drops and rises, when flame turns from detached to attached, then detached again.

Systematic experimental tests were performed to understand the effect of the partial pressure of oxygen ($P_{O_2}$) in the secondary stream on coal jet ignition under an oxy-enhanced environment. During these tests, the following parameters were fixed:

- S.R. = 1.15 = 0.15 primary air + 1.00 secondary air
- Coal feeding rate = 1.95 kg/hr
- Wall temperature = 1361 K
- Secondary stream preheat temperature = 589 K

The following parameters are varied: velocities of both primary air and secondary air, especially the ratios of primary stream velocity ($v_p$) vs. secondary air velocity ($v_s$) to test the burner design. This velocity ratio can affect the turbulent mixing, thus affecting the flame stability [41, 50, 51, 107]. The results of varying this velocity ratio are shown in the following:

1. Under conditions of $v_p/v_s = 1$ ($v_p = v_s = 9.14$ m/s).
Figure 22 and Figure 23 show how flame attachment/detachment changes when varying $P_{O_2}$ in secondary stream under oxy-enriched cases. The difference between Figure 22 and Figure 23 is the velocity.

In Figure 22, both primary jet and secondary jet have higher velocities and higher momentums compared with Figure 23 cases. Higher momentum leads to better turbulent mixing and shorter flame length. While lower momentum generates longer and less luminous flames, which are difficult to measure with the CMOS camera, that relies on the luminosity of the flame.

![Figure 22. Different flame shape under different $P_{O_2}$ in secondary stream when $v_p = v_s = 9.14$ m/s. (a – $30\%$ $O_2$ in secondary stream; b – $24\%$ $O_2$ in secondary stream; c – $21\%$ $O_2$ in secondary stream; d - $30\%$ $O_2$ in secondary stream; e – $21\%$ $O_2$ in secondary stream)](image)

Primary streams are all air and secondary streams are mixtures of $O_2$ and $N_2$. 

The turbulent mixing was the slowest for a velocity ratio of one because the shear stress caused by the velocity gradient between the two layers dominates the turbulent mixing [50, 51].

2. Under conditions of $\frac{v_p}{v_s} = 2$ ($v_p = 9.14 \text{ m/s}; v_s = 4.57 \text{ m/s}$).

Detached flames are always observed when primary jet momentum is higher than secondary jet momentum, as it is difficult for secondary oxidant to diffuse to the primary coal jet to help ignition in the near-burner zone. Therefore, the coal jet must travel a longer time to be well mixed with the secondary oxidant. Few scientists have chosen this ratio lower than one to get better mixing when studying coaxial jet according to Budilarto’s summary [50].
3. Under conditions of $v_p/v_s = 0.5 \ (v_p = 4.57 \text{ m/s}; \ v_s = 9.14 \text{ m/s})$.

More attached flames were observed during the tests when $P_{O_2}$ in the secondary jet is increased. Due to the momentum difference of the primary stream and the secondary stream, better mixing is achieved by the shear stress and turbulence when secondary stream has a higher momentum. Therefore, flame stability is enhanced and the flame is shortened.

Compared with case 1 and case 2, case 3 produces flames which are most easily measured with the optical technique.

At the end of this research phase, the coal feeding rate was adjusted to 4.84 kg/hr to increase the thermal load and reach steady state more quickly. Thus, shortening the flame to lie within the range of optical windows becomes a challenge, which requires a new burner design.

The new burner design used in this study was designed to keep the flame in the range of optical measurement and help stabilize the flame with an optimized velocity ratio under 4.84 kg/hr’s coal feeding rate.

The new operating parameters under air-firing conditions are the following:

$v_p = 5.4 \text{ m/s}, \ v_s = 32.9 \text{ m/s}, \ \text{secondary stream preheat temperature} = 489 \text{ K}, \ v_p/v_s = 1/6.1, \ \text{coal feeding rate} = 4.84 \text{ kg/hr}, \ S.R. = 1.15$, and inside secondary air sleeve Re = 13,300.

Figure 24 shows one of the coaxial burners applied. Figure 25 and Figure 26 show oxy-enriched flames using the above burner design. $P_{O_2}$ in primary stream is kept as 21% (pure air), while $P_{O_2}$ in secondary stream is elevated by injecting pure oxygen to air, namely in these two figures, 28% and 30%.
Figure 24. One of the coaxial coal burners applied. The center pipe is for the primary stream together with coal. The annular sleeve is for the secondary stream.

Figure 25. Flame structure and flame length: A – 28% O₂ in secondary stream; B – 32% O₂ in secondary stream
Figure 26. Flame structure (near-burner view): A – 28% O2 in secondary stream; B – 32% O2 in secondary stream.
4. A METHODOLOGY TO ALLOW QUANTIFICATION OF FLAME STABILITY IN TURBULENT DIFFUSION FLAMES

4.1 An Overview of Flame Ignition Measurement

There are many ways to measure or define flame ignition positions:

1) temperature measurements: ignition is assumed where the temperature sharply increases;

2) CO concentration measurements: ignition is assumed where CO concentration sharply decreases;

3) general optical measurements: such as optical pyrometer, chemiluminescence, etc.

4) laser diagnostics: such as Planar Laser Induced Fluorescence (PLIF) [108-110] and Mie [111].

The first two methods are widely used in field boilers. However, they are not accurate enough in a test of this scale. A probe, such as a suction pyrometer, is not expected to be inserted to the near burner zone and disturb the flame. Ballester et al. reviewed techniques for monitoring flames, either applied to or conceived for monitoring practical combustion equipment. Issues of optical sensors, imaging techniques, pressure transducers, and probing methods were also reviewed. The main challenge in this field is the definition of the most representative flame signals and of their subsequent processing
to derive the meaningful information required to diagnose the state of a flame or to drive a controller in an effective and safe manner [41].

Many researchers have applied optical pyrometers to measure a single coal char particle (size: mm or cm level) ignition temperatures [22, 28, 31, 33, 67, 97, 112]. Chemiluminescence can measure the radicals, such as CH≠, OH, etc., to characterize the ignition [20, 28, 31, 45, 100, 113-122]. Most of the research focuses either on the gas-phase combustion or the single char combustion. Yet regarding larger scale pulverized coal combustion tests, chemiluminescence technology still faces great challenges. One of them is that the intensive radiation due to soot overwhelms the optical measurement area, which makes the chemiluminescence emission hard to detect [123].

Laser diagnostics, such as PLIF, have been widely used in combustion diagnostics. However, few scientists have applied PLIF in a pulverized coal diffusion flame in either the field boiler or pilot scale tests. Recently Hwang et al. performed simultaneous measurement of OH planar laser-induced fluorescence (OH-PLIF) and Mie scattering image of pulverized coal particles in order to examine the spatial relation of the combustion reaction zone and pulverized coal particle. It was a significant advance in PLIF applications on turbulent pulverized coal flames although the flame was actually a methane-coal co-firing flame and the coal feeding rate was only 1.49 × 10⁻⁴ kg/s [109, 110]. The following two problems in applying PLIF in a pilot scale pulverized coal combustor are still challenges to many researchers:

1) The optical window fouling problem is a big challenge for the transmission of laser beams through the “dirty” window [106];

2) Noise due to the particles in the combustion environment of burning pulverized coal is hard to be filtered.
In summary, an economical yet practical methodology, which can effectively quantify flame stability and capture the turbulent fluctuations correlated to ignition, needs to be developed. Due to the complexity of near-burner phenomena, no disturbance is planned to be introduced by applying any probe. Therefore, optical methods are still preferred to carry on this research.

4.2 Selection and Evaluation of CMOS Camera

In recent years, solid-state array sensors have been widely utilized to capture image data in scientific and engineering applications. Array sensors provide a wide range of image qualities and acquisition prices. Often in applications, the knowledge of sensor response to relative light intensity, that is, gray level (GL), is very important. Nowadays, charge coupled device (CCD) and complementary metal oxide semiconductor (CMOS) image sensors are two common technologies for capturing images digitally. Each has unique strengths and weaknesses giving advantages in different applications. Both types of imagers convert light into electric charge and process it into electronic signals. In a CCD sensor, every pixel's charge is transferred through a very limited number of output nodes (often just one) to be converted to voltage, buffered, and sent off-chip as an analog signal. All of the pixels can be devoted to light capture, and the output's uniformity (a key factor in image quality) is high. The CMOS approach is more flexible because each pixel can be read individually. In a CMOS sensor, each pixel has its own charge-to-voltage conversion, and the sensor often also includes amplifiers, noise-correction, and digitization circuits, so that the chip outputs digital bits. These other functions increase the design complexity and reduce the area available for light capture. With each pixel doing its own conversion, uniformity is lower.
Reference [124] compared the differences between CCD and CMOS sensors:

1) CCD sensors create high-quality, low-noise images. CMOS sensors, traditionally, are more susceptible to noise.

2) Because each pixel on a CMOS sensor has several transistors located next to it, the light sensitivity of a CMOS chip tends to be lower. Many of the photons hitting the chip hit the transistors instead of the photodiode.

3) CMOS traditionally consumes little power. Implementing a sensor in CMOS yields a low-power sensor.

4) CCDs use a process that consumes a lot of power. CCDs consume as much as 100 times more power than an equivalent CMOS sensor.

5) CMOS chips can be fabricated on just about any standard silicon production line, so they tend to be extremely inexpensive compared to CCD sensors.

Reference [124] also suggested to choose a CCD camera when working with low light levels or to choose a CMOS camera when working with high light levels.

The camera selected in this research is an EPIX CMOS camera SV5C10 with XCAP-standard software as the control interface. During the tests, camera position (2.2 m away from the optical windows and with the center of lens aligned with the center of the top quartz window) and settings (aperture 6, frame rate 30 fps, and shutter speed 8.3 ms) were fixed all along.

It is very important to understand camera uniformity when performing the optical measurements. Camera uniformity, including the flat field and nonlinearity response of intensified charge-coupled devices, has been widely investigated [20, 65, 122, 125-128]. The work, including the thread of running the image capturing and processing, the evaluation of nonuniformity of an EPIX CMOS camera SV5C10 and comparison
between different camera settings is summarized in Appendix B. Camera sensor non-uniformity and the spatial correlation between pixels and length were evaluated and shown not to cause significant systematic error. Only less than a 1% variation in the estimation of standoff distance was caused.

4.3 Definition of Standoff Distance

Although the visible standoff distance is not necessarily synonymous with ignition location, it should be related to it. Engineers in the field use visual observation of the flame standoff distance to access ignition location of flame stability. In this study, flame stability is quantified by standoff distance (also denoted as liftoff distance), the distance between the burner tip and the visible ignition of the flame. Flame attachment is defined when this distance equals zero. However, as shown in Figure 27, the identification of the flame envelope and flame standoff distance depends on the temporal resolution of the camera. Figure 27 shows the effect of increasing the temporal resolution on images of the ignition zone of the coaxial pulverized coal jet flame. These flame images demonstrate how exposure time and frame rate can affect the determination of the flame structure/envelope. Frames A1 and A2 show flame envelopes with detailed flame structure information missing due to a relatively lower shutter speed (8.3 ms) compared with the one (0.25 ms) applied in frames B1 and B2, which start showing the discrete flame structure. Frame C, captured by a high speed camera using shutter speed of 5 μs, shows the interesting phenomena of the ignition of coal particle/particle groups in the near-burner region. It also shows movements of particles or particle groups and the volatile clouds combustion, which cannot be captured by the human eye or cameras with low shutter speed settings. We have chosen to define flame stability by the standoff
distances observed using the EPIX CMOS camera, with an exposure time of 8.3 ms and a frame rate of 30 fps, rather than attempt to record the very fine fluctuating structure shown in Frame C, because the 8.3 ms shutter speed can correlate with human eyes by the captured flame images. It is important to note that even with the longer exposure times (up to 8.3ms), the standoff distances and flame envelopes still exhibit large low-frequency fluctuations, which in this work are presented as probability density functions (PDFs). Similar issues related to averaging over finite sampling times are present for other techniques that might be employed to quantify flame standoff distances [28, 72, 75, 110].
All the standoff distance data provided in this paper are based on the assumption that quantification of a sufficient number of 8.3 ms images provides a physical description of a coaxial pulverized coal turbulent diffusion flame.

### 4.4 Development of the Methodology

Because inserting a probe in the near-burner zone influences Type 0 PC flames and coal jet ignition, detailed 2D temperature profiles and gas component concentrations are difficult to measure. Therefore, to quantify the flame stability, novel optical measurements and an image processing technique have been developed. The optical methodology developed is targeted as an economical and quantitative solution for measuring flame stability in real industrial applications. Up to now, no similar methodology has been developed in the field to quantify flame stability.

A special CMOS sensor based camera, which is more sensitive to the near infrared wavelength (response: 1.4 V/lux-sec (550nm)), captures Type 0 axial turbulent diffusion flame shape for statistical studies of standoff distance at different operational parameters, such as systematic variations of partial oxygen pressure in both transport and secondary oxidant stream. These statistical analyses are used to understand the effect of oxygen partial pressure in both the transport and the secondary stream on coal jet ignition and flame stability.

The image processing work began with comparing an XCAP-standard commercial software package of EPIX Inc. and Matlab code developed in house. Figure 28 shows the comparison of the results from the different codes. All the pictures have been rotated 90 degrees from the down-fired orientation (left represents the top, while right represents the bottom). The top picture is overexposed in order to test the codes
under extreme conditions. The middle picture shows the result of the first version of Matlab code developed by the oxy-coal combustion group at the University of Utah. The bottom one shows the result by using EPIX XCAP-standard software from the camera vendor. The results show that even under extreme conditions, both the Matlab code and XCAP-standard commercial software can quantify the flame envelope reasonably well. Due to the unfriendly interface and limited ability to process large image sets with XCAP-Standard software, the University of Utah team developed their own Matlab code.

Table 10 shows an example of flame length measurement of an attached oxy-enriched flame, with P_{O2} in secondary stream = 0.28.

Table 11 shows an example of standoff distance and flame length measurements of a detached air-fired flame. In both tables, length means the luminous zone length, while STD represents standard deviation of the measurements. Threshold values range between 0 and 1, and these were manually selected.

A tentative conclusion can be drawn from the results of Table 10 and Table 11: image processing results of flame length and standoff distance depend on selection of threshold value to quantify the flame envelope.
Table 10. An example of flame length measurement of an attached oxy-enriched flame

<table>
<thead>
<tr>
<th>Date</th>
<th>Length(in)</th>
<th>Length STD(in)</th>
<th>Threshold</th>
<th>Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>29-Oct</td>
<td>23.39</td>
<td>2.36</td>
<td>0.45</td>
<td>8</td>
</tr>
<tr>
<td>29-Oct</td>
<td>26.49</td>
<td>2.77</td>
<td>0.80</td>
<td>6</td>
</tr>
<tr>
<td>31-Oct</td>
<td>24.55</td>
<td>4.07</td>
<td>0.28</td>
<td>8</td>
</tr>
<tr>
<td>31-Oct</td>
<td>24.80</td>
<td>4.18</td>
<td>0.80</td>
<td>6</td>
</tr>
<tr>
<td>3-Nov</td>
<td>20.28</td>
<td>2.61</td>
<td>0.42</td>
<td>8</td>
</tr>
<tr>
<td>4-Nov</td>
<td>26.33</td>
<td>5.64</td>
<td>0.50</td>
<td>8</td>
</tr>
<tr>
<td>Average</td>
<td>24.30</td>
<td>2.29</td>
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<td></td>
</tr>
</tbody>
</table>

Table 11. An example of flame length measurements of a detached air-fired flame

<table>
<thead>
<tr>
<th>Length (in)</th>
<th>Length STD(in)</th>
<th>Standoff distance (in)</th>
<th>Standoff distance STD(in)</th>
<th>Threshold</th>
<th>Aperture</th>
</tr>
</thead>
<tbody>
<tr>
<td>14.66</td>
<td>5.21</td>
<td>20.28</td>
<td>3.08</td>
<td>0.26</td>
<td>6</td>
</tr>
<tr>
<td>11.52</td>
<td>5.07</td>
<td>24.00</td>
<td>5.02</td>
<td>0.56</td>
<td>4</td>
</tr>
<tr>
<td>7.16</td>
<td>4.73</td>
<td>26.68</td>
<td>5.77</td>
<td>0.40</td>
<td>6</td>
</tr>
<tr>
<td>13.98</td>
<td>10.04</td>
<td>19.19</td>
<td>5.04</td>
<td>0.40</td>
<td>4</td>
</tr>
<tr>
<td>7.50</td>
<td>10.05</td>
<td>24.59</td>
<td>5.04</td>
<td>0.75</td>
<td>4</td>
</tr>
<tr>
<td>8.83</td>
<td>3.11</td>
<td>24.04</td>
<td>4.54</td>
<td>0.73</td>
<td>4</td>
</tr>
</tbody>
</table>

In order to reduce the effect of manual threshold selection, the University of Utah team updated the image processing code to employ the Sobel (maximum gradient) method to detect the flame edge, which is less subjective. Instead of manually selecting the threshold to convert the grayscale image to the black and white image, the edges of the flame are detected using the Sobel method in Matlab (Figure 29c). This method returns edges at those points where the gradient of the grayscale intensity is at a maximum. The above methodology is shown in Figure 29.
Figure 29. Procedures of flame image processing: (a) original image, (b) image converted to grayscale, (c) edge detection using the Sobel method, (d) image converted to black and white using the threshold calculated from the Sobel method, (e) measurement of image statistics: standoff distance (if any), flame length, and intensity within flame envelope.

This Matlab code was also modified with a lot of efforts to run large sequences of images (i.e., 6000) on the University of Utah’s high-performance computing clusters, Updraft and Uinta. Using the clusters, standoff distances and other statistical analyses for batches of 6000 images could be calculated in approximately 5 minutes, which is about 100 times faster than the single CPU computing. Details on parallel computing and instructions for running this code can be found in Appendix C.
4.5 Determining Sample Size

To determine how statistically representative samples were, two long data sets were collected for both an attached and a detached oxy-fired flame. The visible flame length and flame intensity were statistically analyzed, for the first 500 images, 1000 images, 2000 images, 3000 images, 5000 images, 8000 images and 11,000 images.

For attached flames, the results are shown in Figure 30 and Figure 31. All data sets are normalized to 500-image sample size in order to compare with each other. Even for 500 images, the frequency polygons yield the same trend and values compared with an 11,000-image sample size. The conclusion was that 3000 images are adequate to represent the flame stability. The reason that the averaged intensity within the flame envelope decreases with the long data set is due to the ash accumulating on the quartz windows. The two narrow peaks located beside the main peak in the flame length measurement represent the intervals between quartz windows. According to the code, if a flame edge is located between the intervals of quartz windows, it is assumed to exist in the middle of the intervals.

For detached flames, the standoff distance is of interest. Figure 32 shows the histograms of a long data set of detached flames (an oxy-fired case, overall $P_{O_2} = 40.2$ vol%, $P_{O_2}$ in primary stream = 0). It shows that from the first 500 images to the first 1000, 3000, 5000, 10000, and 11000 images, the histograms yield the same trend. Statistically, the reproducibility of the experiments is good. A total of 3000 is chosen as the sample size. The long bars on the right of Figure 32 show the counts of flames starting in the interval between the top and the middle quartz windows, accounting for approximately 40% of the images.
Figure 30. Histograms of flame intensity within flame envelope for an attached flame (long data set)

Figure 31. Histograms of flame length for an attached flame (long data set)
Figure 32. Histograms of standoff distance of a detached oxy-coal flame (long data set)

4.6 Statistics Applied

In reality, experimental data are often noisy due to operator inconsistency, limitations in instrumentation accuracy, variations of coal feeding rates, etc. In addition to the turbulent nature of a flame, it is always fluctuating. Therefore, two questions need to be addressed:

- How to quantify the accuracy/precision of the experiments.
- How to quantify the reproducibility of the experiments.

With a goal of contributing validation data for large eddy simulation (LES) model development, the quantified precision and accuracy of the OFC experiments are critical. Statistical analyses were performed to begin to quantify the accuracy, error, and reproducibility of the experiments. For instance, Figure 33 shows the histograms of visible flame length of an oxy-coal case (overall $P_{O2} = 40.2$ vol%, $P_{O2}$ in primary stream = 20.7 vol%). It also shows a good repeatability of the experiments.
The major statistical approach applied is a probability density function (PDF). Due to the fluctuating nature of the turbulent flame, a single experimental image, averaged over 8.3ms, is the average of multiple values for standoff distance and flame shape. But this mean value of standoff distance does not sufficiently explain the physics of the unsteady process of pulverized coal jet ignition. Thus, data from 6000 images is presented in the form of a PDF defined by:

$$\rho = \frac{1}{N} \frac{dn_i}{dx_i}$$

where $\rho$ = probability density of standoff distance (cm$^{-1}$), $N$ = the total number of images, $dn_i$ = the number of flames with a standoff distance lifting between $x_i$ and $x_i + dx_i$, and $x_i$ = standoff distance of $i^{th}$ bin (cm).
Other statistical analyses, such as T-statistics and PDF moments, etc., are elaborated and reported in Appendix D.

4.6 Summary of the Methodology

The methodology for quantifying flame standoff distances from the photo-images employed the following procedure:

1. Sequences of images (usually 6000) are taken in 20 seconds by the CMOS camera with camera position and settings fixed;
2. Upload sequences of images to the high-performance clusters;
3. Images are converted into gray scale;
4. Flame edges are detected by using the Sobel method, which returns edges at those points where the gradient of the grayscale intensity is at a maximum;
5. Images are converted into black and white using the threshold values calculated from the average intensity at the edges determined by the Sobel method;
6. Flame statistics, such as standoff distance, are measured in pixels and then converted to cm using the distance at the edge of the window;
7. A PDF, mean and standard error are calculated for the flame standoff distance for each experimental condition.

During the PC ignition process, the sequences of images of flames are taken by a CMOS sensor-based camera with 30 fps. Then, all the images are analyzed by the Matlab code. This code can automatically analyze the following parameters in high-performance clusters:
8. average intensity of the whole image

9. average intensity within the flame envelope

10. visible flame length (luminous zone)

11. mean standoff distance

12. standoff distance at the centerline

13. total area of the flame

14. number of blobs

15. flame width at different locations
5. SCREENING TESTS FOR VALIDATION OF FACILITY AND DEVELOPMENT OF MEASUREMENT TECHNIQUE

The major objective of this chapter is to validate the methodology for air-fired cases, oxy-enriched cases and oxy-fired cases. The purpose was to compare the luminosity, NO\textsubscript{x} formation and flame stability under an O\textsubscript{2}/N\textsubscript{2} environment and an O\textsubscript{2}/CO\textsubscript{2} environment by varying the partial pressure of O\textsubscript{2} in the secondary stream to match the same adiabatic flame temperature.

The burner design parameters are:

- primary sleeve: I.D. = 17.12 mm, $\delta = 2.108$ mm;
- secondary sleeve: I.D. = 42.16 mm, $\delta = 3.556$ mm;
- $v_p$ is always fixed at 5.395 m/s, $v_s$ to $v_p$ ratio varies from 2.5 to 5.4.

The fixed parameters are: Overall S.R. = 1.15 = 0.11 (primary) + 1.04 (secondary); $T_{\text{primary stream}} = 305$ K, $T_{\text{secondary stream}} = 561$ K, $T_{\text{wall}} = 1255$ K, primary $P_{O2} = 21$ vol\%. Coal feeding rate = 10.7 lb/hr = 4.85 kg/hr, Coal type: Utah Bituminous. The testing matrix is shown in Table 12.

Figure 34 shows photo images captured from experiments in O\textsubscript{2}/N\textsubscript{2} environments and O\textsubscript{2}/CO\textsubscript{2} environments. In group I, both air-fired flames and oxy-fired flames are very unstable, making it difficult to identify the flame. This is most likely due to the fluctuations of flame itself instead of fluctuations in the feeding.
Table 12. Cases selected for the comparison between $\text{O}_2/\text{N}_2$ flame and $\text{O}_2/\text{CO}_2$ flame

<table>
<thead>
<tr>
<th>$T_{\text{ad}}$ (K) $\text{O}_2/\text{N}_2$ mixture</th>
<th>Case</th>
<th>$T_{\text{ad}}$ (K) $\text{O}_2/\text{CO}_2$ mixture</th>
</tr>
</thead>
<tbody>
<tr>
<td>$T_{\text{ad}}$ (K) $\text{O}_2/\text{CO}_2$ mixture</td>
<td>No.</td>
<td>secondary $P_{\text{O}<em>2}$ overall $P</em>{\text{O}_2}$</td>
</tr>
<tr>
<td>2334 0.209 0.209</td>
<td>I</td>
<td>2289 0.330 0.313</td>
</tr>
<tr>
<td>2434 0.240 0.236</td>
<td>II</td>
<td>2389 0.380 0.352</td>
</tr>
<tr>
<td>2488 0.260 0.254</td>
<td>III</td>
<td>2447 0.415 0.379</td>
</tr>
<tr>
<td>2528 0.280 0.270</td>
<td>IV</td>
<td>2490 0.445 0.402</td>
</tr>
</tbody>
</table>

Figure 34. Photo images captured from experiments showing the flame attachments/detachments
Figure 35 shows the NO\textsubscript{x} formation when varying P\textsubscript{O2} in the secondary stream. NO\textsubscript{x} was measured at the exit of the exhaust close to the entrance of the stack. The top curve represents O\textsubscript{2}/N\textsubscript{2} flame (both air flame and oxygen enriched flame), which shows the tendency that increasing P\textsubscript{O2} leads to a higher NO\textsubscript{x} formation due to higher temperature. The numbers in the figure show the secondary P\textsubscript{O2} vol\%s. Once the flame becomes attached to the burner, when P\textsubscript{O2} in the secondary stream is higher than 25.4\% in these tests, NO\textsubscript{x} formation is slightly lower, probably due to the different mixing pattern and fluid mechanics caused by the flame attachment. However, the bottom NO\textsubscript{x} formation curve shows that under oxy-coal combustion conditions, NO\textsubscript{x} is not influenced by P\textsubscript{O2} or flame temperature much because theoretically, there is no thermal NO\textsubscript{x} generated without the presence of N\textsubscript{2}. Almost all the NO\textsubscript{x} comes from the nitrogen compounds in the fuel under oxy-coal combustions.

![Figure 35. Comparison of NOx formation under O2/N2 environment and O2/CO2 environment (red and blue numbers show P_O2 in percentage in secondary stream of each case, P_O2 in transport stream is always 20.9%). Error bars are for three replicates for each case. Each replicate contains numerous NOx data.](image-url)
Okumura and Zhang et al. compared the above NOx experimental results with theoretical modeling and drew the following conclusions [129]:

1) In oxy-coal combustion (O2/CO2 atmosphere), the emission of fuel-NOx increases slightly with O2 concentration. This is due to the activation of reactions in which NCO and NH (NOx precursors) are produced, for example, HCN + OH → NCO + H2 and HCN + O → NCO + H; these reactions occur subsequent to the reaction NH + OH → NO + H2 and NCO + H → NH + CO at high O2 concentrations;

2) The flame pattern changes from a detached flame to an attached flame with the increase in flame temperature. The single particle model for estimating NOx emission is applicable to the detached flame pattern. This implies that for the case of the detached flame, pulverized coal burns similarly to a premixed flame;

3) During oxy-coal combustion, the gasification reaction between CO2 and carbon on the surface of char particles occurs more vigorously than during combustion in air.

Figure 36 shows the comparison of the average flame luminosity over the entire image between an O2/CO2 flame and an O2/N2 flame.

Flame luminosity, often related to soot formation in the flame, is of interest if one assumes flame luminosity is proportional to the light intensity, which is calculated from the gray scale of flame images. Consequently when matching adiabatic flame temperature, an O2/CO2 flame tends to be more luminous than an O2/N2 flame, which is contrary to the experimental observations.

To improve the methodology, a new concept of “average intensity within a flame envelope” has been developed.
Figure 37 and Figure 38 show the histograms of average intensity within the flame envelope for an O$_2$/N$_2$ flame and an O$_2$/CO$_2$ flame. The results show that for case IV in Table 12, when an O$_2$/N$_2$ flame and an O$_2$/CO$_2$ flame with an approximately matched adiabatic flame temperature are both attached, the oxy-coal flame is less luminous than the oxygen-enriched flame. This result may indicate that under oxy-coal combustion conditions, less soot is expected, which agrees with our particle group’s work [99]. The intensity traces at short times showed the influence of either attenuation by volatiles or, in some cases, an intense peak attributed to luminous radiation by soot [98].
Figure 37. Histograms of average intensity within flame envelope for an oxygen enriched (O₂/N₂) case IV (see Table 12) attached flame

Figure 38. Histograms of average intensity within flame envelope for an oxy-coal (O₂/CO₂) case IV (see Table 12) attached flame
Figure 39 shows how $P_{O_2}$ in the secondary stream influences flame stability (attachment/detachment) and visible flame length (luminous zone) under oxy-coal combustion conditions. The primary stream partial pressure of $O_2$ is always kept as 20.9%. Increasing $P_{O_2}$ in the secondary stream helped the flame become attached. It also reduced the standoff distance, which also means the coal particles are ignited more quickly. The total flame length is defined here as the sum of luminous zone length and standoff distance. The results may also suggest that when a flame is attached, $P_{O_2}$ may have minor effects on the flame length; however, changing burner operation parameters, such as velocity and momentum, can also influence the flame length [50, 70, 72, 105].

Figure 39. Flame length vs. $P_{O_2}$ in secondary stream under oxy-coal combustion conditions. Error bars are derived from three replicates for each condition.
6. RESULTS

In this chapter, systematic studies of the influence of burner operating parameters on coaxial turbulent diffusion pulverized coal flame stability are reported. The effects of primary \( P_{\text{O}_2} \), secondary preheat, transport media, wall temperature, and overall \( P_{\text{O}_2} \), were all experimentally investigated. A comparison of ignition of different coals was also completed. Most data presented here are for the tests of Utah Bituminous coal and overall \( P_{\text{O}_2} \) no less than 40 vol\%. The tests of PRB coal ignition were also carried out. However, due to the high moisture content, the weak ignition behaviors were difficult to diagnose using the current methodology. An interesting phenomenon, multimodal flame stability, was discovered for the Utah Bituminous coal and is discussed in this chapter. The quantification of flame stability includes PDFs of standoff distances, mean standoff distances, and analysis of multimodal ignition behaviors.

The controlled burner operation parameters are summarized in Table 13 and Table 14. For each test, when varying the primary \( P_{\text{O}_2} \), the adiabatic flame temperature kept relatively constant. The maximum difference between each primary \( P_{\text{O}_2} \) case under the same test group would be no more than 20 K.
Table 13. Conditions for Test 6.1 to 6.5.

<table>
<thead>
<tr>
<th>Test</th>
<th>Pri ( P_{\text{ot}} )</th>
<th>Pri Vel.</th>
<th>Sec. Vel.</th>
<th>Pri. Mom.</th>
<th>Sec. Mom.</th>
<th>CoalMom.</th>
<th>Sec. T</th>
<th>pri. ( O_2 )</th>
<th>pri. ( CO_2 )</th>
<th>sec. ( O_2 )</th>
<th>sec. ( CO_2 )</th>
</tr>
</thead>
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<td></td>
<td>molefr.</td>
<td>m/s</td>
<td>m/s</td>
<td>kg.m/s^2</td>
<td>kg/m/s^2</td>
<td>K</td>
<td>kg/s</td>
<td>kg/s</td>
<td>kg/s</td>
<td>kg/s</td>
<td>kg/s</td>
</tr>
<tr>
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<td>0.000</td>
<td>5.395</td>
<td>14.909</td>
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<td>3.07E-03</td>
<td>4.42E-03</td>
</tr>
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Note: For all these tests, the following parameters were fixed: coal feeding rate 4.84 kg/hr, primary stream temperature 305 K, and wall temperature 1283 K. Test 6.5 had the identical parameters as Test 6.1 A except the wall temperature was 1339 K. Coal concentration was fixed as 1.08 kg/m^3 except in Test 6.4 MM (0.87 – 0.90 kg/m^3).

(pri: primary; sec.: secondary; vel.: velocity; mom.: momentum; T: temperature; molefr.: mole fraction; MV: match velocity; MM: match momentum)
Table 14. Test 6.6 conditions

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Note: For all the above tests, the following parameters were fixed: coal feeding rate 4.84 kg/hr, primary stream temperature 305 K, and wall temperature 1283 K. Coal concentration was fixed as 1.08 kg/m³ except in Test 6.6 MM (0.87 – 0.90 kg/m³).
6.1 Effect of Primary $P_{O_2}$

The objective of this test is to study the effect of primary $P_{O_2}$ on the flame stability. The following operating parameters were fixed: coal feeding rate of 4.84 kg/hr, stoichiometric ratio of 1.15, wall temperature of 1283 K, primary stream velocity of 6.3 m/s, primary stream temperature of 305K, and an overall oxygen concentration of 40 vol%. Two secondary stream preheat values were investigated, 489K and 544K. Variations in primary $P_{O_2}$ were obtained by transferring oxygen flows from primary to secondary CO$_2$ streams, with only small consequent effects on jet momenta. The corresponding conditions can be found in Group 6.1A and 6.1B in Table 13.

Figure 40 shows the flame pictures taken by a family camera Nikon D40 (Camera settings: shutter speed 0.25 ms and frame rate 4 fps) under experiments of Case 4.1A (Table 13). It clearly shows the trend of improved flame stability with increasing primary $P_{O_2}$. From left to right, the $P_{O_2}$ values (in vol%) of the primary O$_2$/CO$_2$ mixture are increased from 0 to 20.7%, as shown in the figure. For each case, two flame pictures are provided here, which indicate that in such an unsteady turbulent ignition process, a single experimental condition results in multiple values for standoff distance and flame shape. Therefore, PDF approach must be applied to quantify data. Figure 41 shows an example of finding ignition points in certain standoff distances with certain probabilities. The left flame picture represents a nearly attached flame while the right one represents a typical detached flame. The PDF figure shows how the flame stability, quantified as standoff distance, varies and oscillates during a short time period in a statistical manner.
Figure 40. Flame pictures of Test 6.1 A (Utah Bituminous Coal, secondary preheat 489K, overall $P_{O_2} = 40\%$, wall temperature 1283 K): increasing primary $P_{O_2}$ helps improve the flame stability. Circular views show the detailed flame structure near the burner.

Figure 41. An example of correlation between real flame pictures and PDF bins.
The various charts in Figure 42 depict the probability that the standoff distance lies within specific limits denoted by the width of the bars. The bars wider than 1 cm (the spatial resolution chosen) represent blind areas where the image was obscured by the top of the quartz window and the burner (on the left) or the break between the two quartz window frames (on the right). Each panel represents a specific primary $P_{O2}$ and secondary stream preheat temperature. On the left-hand side, the panels are for a secondary stream preheat of 489K (yielding a secondary velocity of 14.9 m/s) while the right-hand side represents a secondary stream preheat of 544K (yielding a secondary velocity of 16.6 m/s). Error bars show the fluctuation range of the PDF within the five replicate runs. It is believed that for this scale of experimentation, the small changes caused by shifting $O_2$ from primary to secondary or other small changes did not greatly influence either primary or secondary momenta, according to the numbers in Table 13, and thus, the turbulent mixing between primary and secondary streams can be taken as constant. The major factors determining the flame stability are the primary $P_{O2}$ level and the secondary preheat, which are also going to be discussed in Section 6.2.

One interesting phenomenon observed in the experiments is the multimodal behavior of the PDFs describing flame standoff distances. On any single day, (nominally) identical operating conditions yielded either unimodal and closely positioned bimodal PDFs (signifying attached and nearly attached flames), or widely separated bimodal PDFs (signifying attached flames some of the time and detached flames some of the time). The apparent trimodal behavior is the consequence of averaging these unimodal and bimodal curves. The trimodale PDFs at $T=544K$ are also caused by averaging replicates with bimodal behavior similar to that described above. The observations of bimodal flame stability are shown in Table 15. This flame stability map proves the
Figure 42. Standoff distance PDF profiles of Test 6.1A and 6.1B (conditions shown in Table 12): overall P_{O2} = 40%, Utah Bituminous Coal, each condition includes five replicates.
Table 15. Unimodal/bimodal flame stability observations in Test 6.1A and 6.1B. 0 to 20.7% are primary \( P_{O_2} \) values. Blue, green, and yellow represent flame detachment, bimodal attachment/detachment, and flame attachment, respectively. (U.D.: unimodal detached; B.D.: bimodal detached; B.A.: bimodal attached; U.A.: unimodal attached.)

existence of bimodal flame stabilities in the experiments. Near the transition points of flame stability, the bimodal ignition behaviors (green color) are observed. For Test 6.1A, this transition point was when primary \( P_{O_2} \) was 14.4 vol% while in Test 6.1B, it was 9.9%.

According to Table 15, the multimodal PDFs are real and most probably a result of real multiple steady states which, for example, have been identified by Chen and Churchill for radiantly stabilized gas flames in a refractory tube [130], and may also occur in our system. The experimental setup did not contain influential factors which were not properly controlled. The mode locations are not random (i.e., not the result of random errors in the inputs) and are relatively consistent, which may be due to the large eddies in the combustion chamber.

The individual PDFs for each condition can be found in Appendix C.
6.2 Effect of Secondary Preheat Temperature

At a secondary preheat temperature of 489 K (left column in Figure 42), the flame is detached for all values of primary $P_{O_2}$ below 0.207. At primary $P_{O_2} = 0.144$, there are indications of a few unstable attempts to attach the flame, with very few instances of the flame standoff distance lying at or near the 10cm mark. The lower panel on the left-hand side shows a trimodal PDF curve. The curve is composed of an average of five replicates taken on five different days. The corresponding individual PDFs can be found in Appendix D.

A secondary preheat temperature of 544 K, for an increase of only 55K (right column in Figure 42), greatly improved flame stability. Flame attachment occurs at primary $P_{O_2} = 0.054$. As primary $P_{O_2}$ increases, the flame attachment (the wide bin on the very left) is strengthened, as demonstrated by the diminishing heights of the PDF in the bins on the right. The effect of secondary preheat can be understood as the effect of entrained enthalpy of secondary $O_2$. The enthalpy of $O_2$ at 489 K is 5747 kJ/kmol, while at 544 K, this number is 7466 kJ/kmol, which is 30% higher [131]. The large effect of preheat on flame stability suggests that heat recirculation can also stabilize the flame even at low $O_2$ concentrations in the combusting mixture [85]. The results also support the observation that compensating for the higher molar heat capacity of the gas mixture by increasing the heat supply to the burner quarl can help stabilize a coal flame in a $O_2/CO_2$ mixture [96].

The average standoff distance versus primary $P_{O_2}$ and the comparison between different secondary preheat temperatures are shown in Figure 43. Both Figure 42 and Figure 43 show that under similar turbulent mixing conditions, both primary stream properties ($P_{O_2}$) and secondary stream properties ($T$) affect coal jet flame stability.
Figure 43. The effect of primary $P_{O_2}$ and secondary preheat temperature on average standoff distance.

6.3 Effect of Secondary $P_{O_2}$

The purpose of this test is to study the effect of secondary $P_{O_2}$, with zero $O_2$ in the transport stream, on flame stability. In practical oxy-coal combustion boilers, low oxygen content in the transport stream is favored due to safety concerns. The fixed operating parameters are: primary $P_{O_2} = 0$, coal feeding rate = 4.84 kg/hr, primary stream velocity = 5.4 m/s, wall temperature = 1283 K, primary stream temperature = 305 K, and secondary stream temperature = 489 K. During the test, flame stability (standoff distance) is measured after varying the secondary $P_{O_2}$ by changing the secondary $O_2$ mass flow rate. Examples of flame images under different secondary $P_{O_2}$ conditions taken by a Nikon D5000 (camera settings: shutter speed 0.25 ms, frame rate 4 fps) are shown in Figure 44.
Figure 44. Flame images from Test 6.3 (Utah Bituminous Coal, secondary preheat 489 K, primary PO$_2$ = 0%, wall temperature 1283 K): increasing secondary PO$_2$ helps improve the flame stability. Circular views show the detailed flame structure near the burner. The numbers in the picture represent secondary PO$_2$/overall PO$_2$. For instance, 49%/40% represents secondary PO$_2$ = 49 vol% and overall PO$_2$ = 40 vol%.

The PDF figures of standoff distance are provided in Figure 45. The error bars show the fluctuation range of PDFs in three replicates. The average of the three replicates’ standoff distance versus secondary PO$_2$ is shown in Figure 46. Figure 45 and Figure 46 show how standoff distance decreases and flame stability is enhanced when secondary PO$_2$ increases. Even with zero O$_2$ in the transport stream, the coal jet flame can still be attached when secondary PO$_2$ is greater than 52 vol% and overall PO$_2$ exceeds 43 vol% for these Type 0 flames. Multimodal PDFs were also observed near the transition points when the flame almost attached to the burner tip, as shown in Table 16. As long as the secondary PO$_2$ passes through the transition point (52 vol%), the coal jet flame is
always stable. Thus, this result suggests that practical coaxial oxy-coal jet flames can be stabilized with zero $O_2$ in the transport stream. It also provides additional insight into the effects of diffusion of secondary (preheated stream) enthalpy towards the coal particles initially contained in the primary stream, as will be discussed later.

Table 17 shows the comparisons of turbulent mixing, entrained enthalpies from secondary stream, and the total overall S.R. values. The primary momenta are the same for all cases. The momentum of the secondary stream when secondary $P_{O_2}$ is 52%, which is a transit point for the flame stability, was increased by around 13% compared with the
49% secondary $P_{O_2}$ case, while the entrained enthalpy from the secondary stream kept relatively unchanged. In other words, the turbulent mixing and heat transfer did not change significantly. The effect of changes in parameters in Table 17 brings up the question: which is more important here on flame stability, secondary momentum or overall S.R., or are they equally important? The effect of S.R. can be understood as the different kinetic rates under different overall S.R. values, which represent different global $O_2$ concentrations. The secondary momentum is an important factor which influences the turbulent mixing when primary momentum is fixed. Due to the complexity of the coupling effect between the reaction and the turbulent mixing, it is difficult to address the above question at this phase.
Table 16. Unimodal/bimodal flame stability observations in Test 6.3. 40% to 48% are overall PO2 values. Blue, green, and yellow represent flame detachment, bimodal attachment/detachment, and flame attachment, respectively. (U.D.: unimodal detached; B.D.: bimodal detached; B.A.: bimodal attached; U.A.: unimodal attached.)

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Table 17. Burner Operating Parameters of cases in Test 6.3

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<th>Secondary Momentum (kg·m/s²)</th>
<th>Secondary Enthalpy (kJ/s)</th>
<th>Overall S.R.</th>
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<td>57%</td>
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6.4 Effect of Transport Medium

The objective of this test is to evaluate the hypothesis that transport through the primary medium might control the ignition of coaxial pulverized coal jets and that this can affect coal-jet ignition upon transitioning from air-fired to oxy-fired conditions. In this test, only the oxy-coal O2/CO₂ transport stream is replaced by an O₂/N₂ mixture. The secondary stream remains O₂/CO₂. Two matching criteria, either momenta or velocities [50, 68], are selected to perform the test to compare with the tests discussed in Section 4.1. The momentum selected here only represents the primary stream flow’s excluding the coal particle momentum. The solid phase momentum is also shown in Table 13. The fixed operating parameters are: coal feeding rate = 4.84 kg/hr, overall PO2 = 40 vol%, wall temperature = 1283 K, and secondary preheat temperature = 489 K. The standoff distance data expressed as PDFs is supplied in Figure 47. Multimodal behaviors of the
Figure 47. Standoff distance probability density function profiles of Test 6.4: using O₂/N₂ mixture as the transport stream. Two criteria are chosen for transport stream to compare with test 6.1A: matching momentum (left column) and matching velocity (right column).
PDFs describing flame stability are reported in Table 18. The improved flame stability was due to the introduction of N\textsubscript{2} in the transport stream. The corresponding mechanism is going to be discussed in Chapter 7.

Figure 48 shows the average standoff distance data when varying P\textsubscript{O2} in the transport stream. Error bars represent the three replicates. Rectangular data points show the results of Test 6.1A where secondary preheat temperature is 489 K. The corresponding PDF data can be found in the left column of Figure 42. Circular data points show the average standoff distance values of the right column of Figure 42 when the secondary preheat temperature is 544 K (Test 6.1 B). The bottom two series of triangular data points show the results of the tests discussed in this section by matching either momentum (denoted by MM) or velocity (denoted by MV) of the primary stream compared with the test discussed in Section 6.1, when secondary preheat temperature is 489 K. Although different matching criteria lead to different flame stabilities at low primary P\textsubscript{O2} levels due to different turbulent mixing effects, using O\textsubscript{2}/N\textsubscript{2} mixture as the transport stream creates a vast improvement in flame stability, especially when the primary (transport) P\textsubscript{O2} level is greater than 9.9 vol%.

These results are consistent with those of Heil et al., who reported that in swirl-stabilized flames, the use of air as the primary stream led to flame stabilization at lower O\textsubscript{2} levels compared to using O\textsubscript{2}/CO\textsubscript{2} as the primary stream [96]. The matching velocity case has better flame stability because it has a lower mass flow rate than the matching momentum case. According to Heil et al. [96], decreasing the mass flow through the burner can increase the ratio of recirculated flue gas around the jet and incoming gas mixture from the burner. This generates under-stoichiometric conditions in the near burner region and increases the flame temperature, which enhances the reaction rates.
Table 18. Unimodal/bimodal flame stability observations in Test 6.4. The numbers of 0 to 20.7% are primary P_{O2} values. Blue, green, and yellow represent flame detachment, bimodal attachment/detachment, and flame attachment, respectively. (MM: match momentum; MV: match velocity; U.D.: unimodal detached; B.D.: bimodal detached; B.A.: bimodal attached; U.A.: unimodal attached.)

<table>
<thead>
<tr>
<th>Test 6.4 MM</th>
<th>P_{O2} = 0</th>
<th>P_{O2} = 5.4%</th>
<th>P_{O2} = 9.9%</th>
<th>P_{O2} = 14.4%</th>
<th>P_{O2} = 20.7%</th>
</tr>
</thead>
</table>

<table>
<thead>
<tr>
<th>Test 6.4 MV</th>
<th>P_{O2} = 0</th>
<th>P_{O2} = 5.4%</th>
<th>P_{O2} = 9.9%</th>
<th>P_{O2} = 14.4%</th>
<th>P_{O2} = 20.7%</th>
</tr>
</thead>
</table>

Figure 48. Average standoff distance vs. primary P_{O2}: a comparison between primary O_{2}/CO_{2} mixture and primary O_{2}/N_{2} mixture. The error bars presented for O_{2}/CO_{2}-489K case are too small to be visible.
The comparison between the “matching velocity” case and the “matching momentum” case revealed the effect of different turbulent mixing on the flame stability.

Kiga et al. found in their microgravity measurements of the combustion of coal clouds in 40% O\textsubscript{2} with N\textsubscript{2}, CO\textsubscript{2}, and Ar as the background gas, the flame propagation speed increased in the order of Ar > N\textsubscript{2} > CO\textsubscript{2} but it could be increased by increasing O\textsubscript{2} concentration in CO\textsubscript{2} [81]. Since one of the criteria of flame stabilization is that the flame propagating speed should be higher than the local mixture velocity, the results in reference [81] provide another insight into the different stabilities in different primary mixture environments.

Figure 49 and Figure 50 show the detailed flame structure images taken from the experiments by a Nikon D5000 (shutter speed: 0.25 ms, frame rate: 4 fps). Even for the same flame attachment under different primary P\textsubscript{O2}s, flame shape, structure, and temperature, and NO\textsubscript{x} formations, etc. are different. The O\textsubscript{2}/N\textsubscript{2}/CO\textsubscript{2} flame is hotter than the O\textsubscript{2}/CO\textsubscript{2} in the near burner region which is due to the better ignition. Correspondingly, the NO\textsubscript{x} formation of the former is 10% to 20% higher than the one of the latter due to the higher temperature and the presence of N\textsubscript{2} contributing to the thermal NO\textsubscript{x} in the near burner region. Furthermore, this diffusion flame tends to be wider, stronger, and more luminous in the near burner zone with the replacement of primary CO\textsubscript{2} by N\textsubscript{2}, as shown in the circular views of Figure 49 and Figure 50. With the presence of N\textsubscript{2}, the diffusion of O\textsubscript{2} through the background media to the surface of coal particles seems to be faster than the cases in Test 6.1A, according to the fact described above. For the “matching velocity” case, even with zero P\textsubscript{O2} in the primary stream (pure N\textsubscript{2}), the flame stability is better than the corresponding case with pure CO\textsubscript{2} in the primary stream. In this test, the replacement of CO\textsubscript{2} by N\textsubscript{2} has a stronger effect on the flame stability than the turbulent mixing effect.
Figure 49. Flame images of Test 6.4 “matching momentum”

Figure 50. Flame images of Test 6.4 “matching velocity”
according to the comparison between the “matching momentum” case and “matching velocity” case.

6.5 Effect of Wall Temperature

Wall temperature is another degree of freedom during the pulverized coal ignition process, which may impact the flame stability of this test. However, due to the reliability concern, as mentioned earlier, the wall heaters installed in this furnace can only operate up to about 1400 K when exposed to the hot oxidizing environment. Therefore, there is little room for adjusting wall temperature to a relatively high level in order to protect the heating element. This is the major reason for our wall temperature setting being always fixed at 1283 K (1850 F).

With great caution, another test was conducted to compare with Test 6.1A (see Table 13). All the parameters were set to be identical to Test 6.1A except the wall temperature, which was set to 1339 K (1950 F). Figure 51 shows that under a higher wall temperature, the ignition of the coal flame is enhanced and thus the flame became attached when primary $P_{O_2}$ was 5.4%. Compared with Test 6.1A and 6.1B, wall temperature contributes a more significant effect on flame stability. In Test 6.1A, the flame became attached when primary $P_{O_2}$ was up to 20.7%. In Test 6.1B, increasing secondary preheat temperature helped the flame stabilize at a primary $P_{O_2}$ of 9.9%.

Figure 52 further compares the difference between 1283 K wall temperature and 1339 K wall temperature. With all other parameters fixed, increasing wall temperature (case notations start with B) significantly improved the ignition behavior with a better flame stability, a stronger and hotter flame zone, and a higher flame luminosity. It is believed that a hot wall provides a heating source for not only the radiation to coal
Figure 51. Flame pictures with the wall temperature set to 1339K. All other parameters were set identical to Test 6.1A (see Table 13).

Primary $PO_2 = 0\%\ 5.4\%\ 9.9\%\ 14.4\%\ 20.7\%$

Figure 52. Using flame pictures to compare the effect of wall temperature. B1: Primary $PO_2 = 20.7\%$ case in Test 6.1A (see Table 13), wall temperature 1278 K; A1: Identical to A1 except wall temperature 1339 K; B2: Secondary $PO_2 = 50\%$ case in Test 6.4 Matching Velocity, wall temperature 1278 K; A2: Identical to A2 except wall temperature 1339 K.
particles, but also the convection to the flue gas near the wall driven by internal recirculation. Therefore, controlling the wall temperature can help determine the effect of this independent variable on flame stability.

Due to the reason that 1339 K is close to the wall heater’s operation limit, this test was not repeated. Figure 53 shows the PDF data of 1339 K wall heating. Figure 54 shows the effect of wall temperature on the measured mean standoff distance.

6.6 Effect of Overall P\textsubscript{O}\textsubscript{2}

In this test, a different overall P\textsubscript{O}\textsubscript{2} value, 32 vol\%, has been applied to repeat the conditions in the previous Sections 6.1, 6.2, and 6.4, in which the overall P\textsubscript{O}\textsubscript{2} was fixed as 40 vol\%. The meaning of selecting 32% overall P\textsubscript{O}\textsubscript{2} is to match the same adiabatic flame temperature as air-firing conditions. The corresponding operation parameters can be found in Table 14.

As expected, in the 32% overall P\textsubscript{O}\textsubscript{2} cases, the flame stability was worse than in the 40% overall P\textsubscript{O}\textsubscript{2} cases. It was difficult to capture the ignition behavior in the near burner region (the top quartz window) and therefore, no standoff distance PDF profiles are available at this point. Although 6000 images were taken for each replicate, very few images (less than 10% of total images) show the ignition scenes with the area of interest (AOI) of the camera focused in the top window, except the higher primary P\textsubscript{O}\textsubscript{2} cases in Test 6.6 MM and 6.6 MV (see Table 14). Figure 55 and Figure 56 show the corresponding flame images taken from the experiments.

It is very difficult to stabilize the flame in O\textsubscript{2}/CO\textsubscript{2} environments when matching the adiabatic flame temperature with the air-firing case with a coaxial burner setup.
Figure 53. Standoff distance PDF profiles of 1339 K wall heating. Other parameters except the wall temperature are identical to Test 6.1A.
Primary $P_{O_2}$ and secondary preheat temperature have limited effects on flame stability due to the high concentration of CO$_2$ in the combustion oxidant. The total gas feeding rate and the total momentum entering the combustion chamber are higher than the 40% overall $P_{O_2}$ cases, which contributes to a further ignition distance. Thus, practically advanced mixing mechanisms, such as swirl and bluff body, must be introduced to improve the mixing and help stabilizing the flame.

It is also interesting to observe that changing the transport media from O$_2$/CO$_2$ mixture to O$_2$/N$_2$ mixture play a big role in stabilizing the flame, as shown in Figure 55 and Figure 56. This observation provides further proof that the pulverized coal ignition and combustion are diffusion controlled under O$_2$/CO$_2$ environment [28, 33, 45, 97].
Figure 55. Flame pictures of Test 6.6 MV (see Table 14): primary stream O₂/N₂, secondary stream O₂/CO₂, matching primary velocity with Test 6.6A.

Figure 56. Flame pictures of Test 6.6 MM (see Table 14): primary stream O₂/N₂, secondary stream O₂/CO₂, matching primary momentum with Test 6.6B.
6.7 Effect of Coal Type

To study the effect of coal composition, Power River Basin (PRB) coal, one type of lignite coals, was experimentally studied in this work to compare with Utah Bituminous coal. Great difficulty was encountered when applying the current methodology to quantify the flame envelope. It was observed that the PRB coal was very difficult to ignite during the test. This is primarily due to its high moisture content, which is about 21% mass weight. Thus, PRB coal particles have a longer residence time to heat up, dry the moisture, and then accomplish the devolatilization process to finally ignite.

The flame luminosity of PRB coal is low because the high moisture content inhibits soot formation. This image processing technique did not work well due to its dependence on quantifying the gradient of the intensity of the flame, which is proportional to the flame luminosity, while the soot generated in bituminous coal, acting as nearly black bodies, contributes to the visible spectrum and near infrared radiation, making the ignition detectable by applying the optical measurement. The poor ignitability of PRB flame is shown in Table 19.

Table 19. Image processing results for PRB Coal. The AOI was still focused in the near burner region. The numbers in the table show how many images out of 6000 have flame/ignition scenes. Most of the images are blank. Data collected from July 21 to August 4 (green) represent the overall P_{O2} as 40%, while data collected from August 17 to August 19 (blue) represent the 32% overall P_{O2} cases. Results show the poor ignitability of PRB flame.
Kurose et al. studied the effect of moisture in coal on pulverized coal combustion characteristics [83]. They found that as the moisture increases, flame temperature and NOx mole fraction decrease while O2 mole fraction increases in the region near the burner, and the peaks of the flame temperature and NOx mole fraction shift downstream, delaying the ignition. Also, the increase in the moisture increases the unburned carbon fraction and decreases the NOx conversion at the outlet of the furnace [83].

In summary, the comparison between Utah Bituminous coal and PRB coal can be concluded:

1) Although PRB coal may be more active when dried, the flame stability of PRB coal is much worse than Utah Bituminous coal due to the high moisture content, which made this comparison unfair.

2) Since the soot generated in the PRB flame is less than the one in Utah Bituminous, instead of using the current methodology, the chemiluminescence measurement of the radicals released in the early stage of ignition, such as OH, C* and CH*, is suggested.

3) The comparison between bituminous coal and subbituminous coal with similar moisture content is suggested in the future, especially with the safety concern of drying PRB coal in the lab.
7. DISCUSSION

In this chapter, the effect of O$_2$/N$_2$ versus O$_2$/CO$_2$ environment on mechanisms is discussed. The objective is to analyze different mechanisms influencing the ignition and flame stability in order to better understand which mechanism is more important during the ignition compared with others. This chapter includes calculations and analyses of equilibrium aspects, thermal conductivity effects, and diffusivity effects. The experimental data is correlated to understand the transport medium effect on flame stability. The scaling analysis of the physical and chemical processes inside the combustor provides an insight into different mechanisms by estimating their time or length scales. Local O$_2$ concentration in the coaxial jet flame is also estimated to understand the mixing process without the in-flame measurements in the near-burner region.

Molina and Shaddix compared the ratios of several thermophysical properties and some nondimensional groups for N$_2$ and CO$_2$, as calculated for a temperature of 1200 K using CHEMKIN [28, 132], as shown in Figure 57. Their work provides a good start to make the comparison.

7.1 Equilibrium Aspects

As known, there are two major criteria in matching the air-firing condition with the oxy-firing condition: adiabatic flame temperature and heat flux. Due to the difference
of heat capacities ($C_p$) between $N_2$ and CO$_2$, the adiabatic flame temperature and equilibrium temperature under varied environments are different. Figure 58 shows the results of this comparison. The equilibrium temperature is always lower than the adiabatic flame temperature due to the dissociation reactions, especially without the presence of CO$_2$ in the combustion oxidant stream. Under O$_2$/CO$_2$ environment, CO$_2$ can react with the carbon surface, which moves the reaction further forward. With a 50% heat loss, the so-called adiabatic flame temperature and equilibrium temperature are very close to each other because the combustion reaction is exothermic. The green solid lines show that to match the air-firing conditions, about 31% $P_{O_2}$ in oxy-firing should be realized. It is interesting to point out that matching the adiabatic temperature can lead to matching the total heat loss/removal. The result of this theoretical calculation is consistent with the experimental results from a lab-scale oxy-coal fluidized bed [133].
Figure 58. Comparison of adiabatic flame temperature and equilibrium temperature between O$_2$/N$_2$ environment and O$_2$/CO$_2$ environment. Red color represents zero heat loss. Blue color represents 50% heat loss (OFC reactor’s heat loss is estimated as 50% to 60%). The meanings of the notations are: nd – nondissociation; eq – equilibrium; CO$_2$ – O$_2$/CO$_2$ environment, N$_2$ – O$_2$/N$_2$ environment. When heat loss is zero, the nondissociation temperature also means the adiabatic flame temperature. Coal type: Utah Bituminous. Primary P$_{O2}$ is 0. Primary stream temperature is 305 K, while secondary stream temperature is 544 K. Initial Coal temperature is 305 K. Total S.R. is 1.15. Heat Capacity of the ash in coal is 2800 J/kg-K. No gasification is assumed and the coal conversion ratio in combustion is 1.
7.2 Heat Capacity ($C_p$) Effect or Thermal Conductivity ($\lambda$) Effects

After coal is injected to the reactor, the first phenomenon is particle heat up from ambient temperature to a gas temperature at which volatiles begin to be released [28]. Molina and Shaddix used the following equation to describe a nonreactive particle heat up process:

$$\frac{dT_p}{dt} = \frac{-3}{C_p\rho_P r_P^2} \left[ \varepsilon \sigma (T_p^4 - T_w^4) + h(T_p - T_g) \right]$$  \hspace{1cm} \text{(equation 7-1)}

where $T_p$, $T_w$, and $T_g$ are the particle, wall, and gas temperature, respectively; $C_p$, $\rho_P$, $r_P$, and $\varepsilon$ are particle heat capacity, density, radius, and emissivity, respectively. $\sigma$ is the Stefan-Boltzmann constant and $h$ is the coefficient for convection heat transfer. The gas-to-particle radiant transport because of the hot CO$_2$ and H$_2$O is neglected due to the small scale of their reactor [28]. This equation shows that the wall temperature ($T_w$) and the secondary preheat temperature ($T_g$) affect the particle heat up and the wall temperature has an effect of fourth power magnitude on the particle heat up rate. This can explain the reason that the effect of the wall temperature on ignition is more significant than the secondary preheat temperature, as shown in Section 4.5. For our tests, when the wall temperature ($T_w$) and the secondary preheat temperature ($T_g$) are fixed, the only possible effect of the different gas mixtures on initial particle heating resides in the coefficient of convection heat transfer, $h$, which can be calculated from the equation of $N_u = hD/\lambda$, where $N_u$ is Nusselt number and can be assumed as 2, $D$ is the particle diameter, and $\lambda$ is the gas thermal conductivity. Therefore, the only gas property affecting the initial particle heating-up is the thermal conductivity [28].
This conclusion can also be derived from the equation of characteristic time for particle heat up. If this characteristic time $\tau_{\text{heat}}$ is defined as

$$
\frac{(T_{p0} - T_g)}{(T_{p,\text{heat}} - T_g)} = e,
$$

(equation 7-2)

where $T_{p0}$ is the initial particle temperature, $T_g$ is the gas temperature, $T_{p,\text{heat}}$ is the particle temperature at the moment of the characteristic time, and $e$ is the mathematical constant, then the equation for this characteristic time is,

$$
\tau_{\text{heat}} = \frac{\rho_p C_p D_p^2}{(6N_u \lambda g)}
$$

(equation 7-3)

where $C_p$, $\rho_p$, $D_p$, and $N_u$ are particle heat capacity, density, diameter, and Nusselt number, respectively; $\lambda$ is the gas thermal conductivity and $g$ is the acceleration due to gravity. For a constant particle size and Nusselt number of 2, the characteristic time only depends on the thermal conductivity of the gas surrounding the particle. The equation of characteristic time of initial heating up also shows the importance of considering the effect of different particle sizes during the ignition. The time needed to reach the characteristic time is proportional to the particle surface area.

These two processes following the particle heat up can occur: the onset of heterogeneous ignition of the coal particle or the release and the ignition of volatiles [15-17, 19, 20, 23, 25, 28, 31-34, 37, 97]. For certain cases, initial heterogeneous ignition can be quenched by the eruption of volatiles [15]. In bench scale tests, whether the coal particle is ignited homogeneously or heterogeneously is very much dependent on the control of experimental conditions [17, 20, 28, 31, 32, 41, 46, 47, 99].
If only considering homogeneous ignition of coal particles, the volatiles release process follows the initial particle heat up. Since coal devolatilization is an endothermic process whose rate is strongly dependent on particle temperature and particle heating rate, particles having similar heating profiles before the devolatilization for the different gas mixtures, as discussed earlier, will experience a similar onset time for coal devolatilization [28]. The process of homogeneous gas-phase ignition is also dependent on the transport properties of the surrounding gas and the combustion heat release and the reactivity of the fuel-oxidizer mixture [28]. For coal particles introduced into a hot atmosphere, ignition presumably occurs in a localized region where the combination of gas temperature, oxygen concentration, and volatile concentration undergoes autoignition. Ignition time decreases when the mixture reactivity and heat release increase, and increases when the product of heat capacity and density ($\rho C_p$) increases. Here $\rho C_p$ is a measure of the thermal sink for any heat that is chemically released. According to Figure 57, $\rho C_p$ of CO$_2$ is 1.7 times the one of N$_2$. Therefore, the volatiles released into an N$_2$ atmosphere will ignite more quickly than those released into a CO$_2$ environment. This may be a reason for the standoff distances decreased when replacing primary CO$_2$ by N$_2$. On the other hand, a higher O$_2$ concentration decreases ignition time by increasing the characteristic reaction rate of the local mixture [28]. This theory is also consistent with our results discussed earlier.

7.3 Diffusivity (D) Effects

Field et al. commented in their book,

Unless the fluid velocity is constantly changing – as in a cyclonic flow or in the pulsating combustor – any initial relative motion between particle and gas does not long persist, and the accelerations involved in normal gas turbulence such as is encountered in jet mixing or in turbulent flow through
furnaces is not sufficiently great to result in relative motion of solids and gas. Even if the relative velocity is as high as 20 m/s, the particle Reynolds number for flow around a sphere 50 in diameter would be only 10. This is in agreement with the statement, that close to the particle surfaces the transport of gases is dependent on molecular diffusion. [35]

This statement shows that even under turbulent mixing, the molecular diffusion of O₂ to the particle surfaces still play a big role during ignition and combustion.

During homogeneous ignition, once the volatiles cloud is ignited, a diffusion flame provides additional heating of the particle and consumes the evolved volatiles. Molina and Shaddix used the quasi-steady droplet combustion theory [134] to express the mass consumption rate as \( m = (4\pi r_s^3) \times \rho_s D \times \ln (1 + B) \), where \( r_s \) is the droplet radius, \( \rho_s \) is the fuel vapor density at the particle surface, \( D \) is the fuel mass diffusivity, and \( B \) is the Spalding transfer number [28]. \( B \) can be given by:

\[
B = \left( \frac{Y_{O,\infty}}{OF} \right) \frac{h_C}{h_V} + \left[ C_p(T_\infty - T_s) \right] \], where \( T_\infty \) is the bulk gas temperature, \( Y_{O,\infty} \) is the mass fraction of oxygen in the bulk gas, \( OF \) is the stoichiometric mass oxygen-fuel ratio, \( h_C \) is the heat of combustion of fuel vapor, \( h_V \) is the heat of vaporization (or devolatilization for coal particle ignition case) of the drop, and \( C_p \) is the heat capacity of the volatilized fuel here.

Therefore, replacing \( N_2 \) with \( CO_2 \) only influences the consumption rate of the volatiles through its impact on the diffusivity of CH₄ [28]. The volatile consumption in \( CO_2 \) is slower than in \( N_2 \) according to the diffusivity comparison of CH₄ in \( N_2 \) and in \( CO_2 \) shown in Figure 57. When \( O_2 \) concentration is higher, this volatile consumption rate is also higher.

During the heterogeneous ignition, the \( \rho C_p \) effect can be ignored because the process involves \( O_2 \) directly attacking the carbon surface and then reacting with the carbon. Thus, the factors are \( O_2 \) diffusion to the char surface, char reactivity, and reaction kinetics. Char reactivity depends on the coal type, while reaction kinetics mainly depends
on the temperature and O₂ concentration. Near the particle surface, especially in the boundary layer, the transport of O₂ to the particle surface is dominated by the diffusion process. Therefore, under different gas environments, the O₂ diffusion process is very important and has been reported both experimentally [33, 97] and theoretically [38-40].

Table 20 shows the oxygen diffusion coefficients of binary gas pairs at atmospheric pressure and under two temperatures [135]. It shows that at low temperatures, the diffusivity of O₂ in N₂ is about 40% higher than that in CO₂. For a ternary mixture, say O₂/CO₂/H₂O (g), the O₂ diffusion coefficients are calculated in Table 21 [135] for variations of O₂, relative humidity, and temperature. For each calculation, increases in the O₂ mole fraction are assumed to be offset by CO₂ increases in the calculation. The oxygen concentration enters the diffusion equation in two ways, both embedded in the diffusion coefficient and as the driving force through its concentration gradient. As the driving force, oxygen concentrations do have a very significant effect on the magnitude of diffusive oxygen transport [135].

Table 20. Oxygen diffusion coefficients of binary gas pairs at atmospheric pressure

<table>
<thead>
<tr>
<th>Binary Pair</th>
<th>Temperature (°C)</th>
<th>Diffusion Coefficient (cm²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>O₂ – CO₂</td>
<td>20</td>
<td>0.153</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.193</td>
</tr>
<tr>
<td>O₂ – H₂O (vapor)</td>
<td>20</td>
<td>0.240</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.339</td>
</tr>
<tr>
<td>O₂ – N₂</td>
<td>20</td>
<td>0.219</td>
</tr>
<tr>
<td></td>
<td>60</td>
<td>0.274</td>
</tr>
</tbody>
</table>
Table 21. Effect of temperature and gas mixture on oxygen diffusion coefficients

<table>
<thead>
<tr>
<th>Temperature(°C)</th>
<th>Relative Humidity</th>
<th>O₂ Diffusion Coefficient (cm²/s)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>at 2% O₂</td>
</tr>
<tr>
<td>20</td>
<td>50%</td>
<td>0.203</td>
</tr>
<tr>
<td>20</td>
<td>100%</td>
<td>0.203</td>
</tr>
<tr>
<td>60</td>
<td>50%</td>
<td>0.259</td>
</tr>
<tr>
<td>60</td>
<td>100%</td>
<td>0.264</td>
</tr>
</tbody>
</table>

7.4 Data Correlation for Transport Medium Effects on Flame Stability

In the previous subsection, the fundamentals of O₂ diffusivity in different gas/gas mixtures were discussed. In this subsection, a simple diffusion model is developed to discover the time needed for P₀₂ at the coal particle surface to reach ignition points and to correlate the theoretical calculation of ignition time to the measured standoff distance of the turbulent flames. The objective is to justify that even under turbulent mixing, the molecular diffusion of O₂ to the particle surfaces is the controlling mechanism during ignition and combustion.

This model is designed to yield the following physical view of the interactions between turbulent mixing and coal particle ignition mechanisms: large eddies transport packets of coal particles, and their surrounding primary fluid, into the secondary fluid. The primary oxygen concentration determines the initial concentration of O₂ at the particle surface. In order for the coal to ignite, this must be increased to a required ignition level of O₂ at the surface through molecular diffusion of oxygen to the particle surface. This molecular diffusion flux through a film of primary fluid is enhanced by a) increases in the concentration of O₂ in the secondary fluid, and b) increases in the diffusion coefficient of O₂ in the primary fluid (N₂ versus CO₂). Figure 59 shows a one-
A mass diffusion model to predict the time needed for $P_{O_2}$ at the particle surface to reach certain values.

The mass transfer equation can be written as (no convective flux, no heat transfer and no reaction),

$$\frac{\partial C}{\partial t} = D \left[ \frac{1}{r^2} \frac{\partial}{\partial r} \left( r^2 \frac{\partial C}{\partial r} \right) \right] \tag{equation 7-4}$$

where $C$ is the $O_2$ mole fraction, and $D$ is the diffusivity of $O_2$ in the binary mixture.

To simplify the model, we assume a constant temperature of 60°C (since mass transfer diffusivity is a weak function of temperature), and the initial $O_2$ mole fraction is $C_0$ and uniform everywhere in the thin layer. The coal particle radius is 100 μm and so is the film thickness. Outside the thin film, the $O_2$ concentration is suddenly increased to $C_2 = 0.40$ (mole fraction) and kept constant (boundary condition 1). At the surface, the gradient of $O_2$ mole fraction is kept as 0 (boundary condition 2). Then, the transient state
is solved in Comsol 3.5 to find out the time needed for $P_{O2}$ at the particle surface to reach a certain value. The binary mixtures of $O_2/N_2$ and of $O_2/CO_2$ are both studied to compare with each other, as shown in Figure 60. The x-axis is the targeted $P_{O2}$ level at the surface. The y-axis represents the time needed. $O_2$ diffusivity values can be found in Table 20 when assuming a constant temperature of 60 °C. The results show that under conditions investigated, the time needed is usually at the magnitude of $10^{-4}$ s.

Figure 60. The comparison of $O_2$ diffusion in $N_2$ and in $CO_2$: time needed for $O_2$ diffusing to the particle surface to reach certain concentrations.

Table 22 shows that

$$\frac{t_{O2/N2}}{t_{O2/CO2}} = \frac{D_{O2 in CO2}}{D_{O2 in N2}}$$

(equation 7-5)
Table 22. The ratio of the time needed in O₂/CO₂ mixture vs. that in O₂/N₂ mixture.

\[ \frac{D_{O₂ \text{ in } N₂}}{D_{O₂ \text{ in } CO₂}} = 1.42 \text{ at } 60 \degree C \text{ and } 1 \text{ atm.} \]

<table>
<thead>
<tr>
<th>Initial ( P_{O₂} ) (vol%)</th>
<th>5.4</th>
<th>9.9</th>
<th>14.4</th>
<th>20.9</th>
<th>24.3</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>1.42</td>
<td>1.42</td>
<td>1.43</td>
<td>1.42</td>
<td>1.42</td>
</tr>
<tr>
<td>5.4</td>
<td>1.42</td>
<td>1.42</td>
<td>1.42</td>
<td>1.42</td>
<td>1.42</td>
</tr>
<tr>
<td>9.9</td>
<td></td>
<td>1.42</td>
<td>1.42</td>
<td>1.42</td>
<td>1.41</td>
</tr>
<tr>
<td>14.4</td>
<td></td>
<td></td>
<td>1.41</td>
<td>1.41</td>
<td></td>
</tr>
<tr>
<td>20.9</td>
<td></td>
<td></td>
<td></td>
<td>1.42</td>
<td></td>
</tr>
</tbody>
</table>

where \( t_{O₂\text{N₂}} \) and \( t_{O₂\text{CO₂}} \) are the times needed for \( P_{O₂} \) at the particle surface to reach a certain level in \( O₂/N₂ \) and \( O₂/CO₂ \) mixtures, respectively; \( D_{O₂ \text{ in } CO₂} \) and \( D_{O₂ \text{ in } N₂} \) represents O₂ diffusivities in different background gases. This is because the characteristic time for diffusion is usually quantified as \( L^2 / D \), where \( L \) is the characteristic length and \( D \) is the diffusivity. In our comparison, the characteristic length is fixed when comparing between \( O₂/N₂ \) case and \( O₂/CO₂ \) case. Therefore, the comparison of the time needed for diffusion process in different gases is actually the comparison of the different corresponding diffusivities.

In the above calculations, secondary \( P_{O₂} \) is fixed as 40 vol%. In the following discussions, the boundary conditions of primary \( P_{O₂s} \) (\( C_0s \)) and secondary \( P_{O₂s} \) (\( C_2s \)) are adjusted to be identical to the conditions in the experiments, as shown in Table 13. Assuming primary \( P_{O₂} = 14.4\% \) at the particle surface is the ignition criterion, the correlation between the measured mean standoff distance and the predicted ignition time, as shown in Figure 61 and Figure 62, indicates that even in the turbulent diffusion coal flame of this scale, coal ignition and flame stability are still diffusion controlled. Matching momentum is a better approach when comparing between \( O₂/N₂ \) environment.
Figure 61. The measured mean standoff distance vs. predicted diffusion time to reach ignition point. The comparison for Test 6.1B and Test 6.4 MM (see Table 13) shows the difference between carrier gases. Data show the trend of diffusion controlling on the turbulent diffusion coaxial coal jet ignition and flame stability.

and O₂/CO₂ environment than matching velocity at this point. The results shown here agree with Field’s statement, that close to the particle surfaces, the transport of gases is dependent on molecular diffusion [35]. The results also agree with the diffusion-limited mechanism in references [28, 33, 45, 97, 136] and suggest that for better coaxial flame stability, primary Pₐ should be no less than 14.4 vol%.

Figure 61 also shows that the measured standoff distance is correlated to the diffusion time needed for O₂ diffusing from the secondary stream to the primary stream even under different environments of transporting media. The momenta of transporting streams were matched for two different transporting media (O₂/N₂ and O₂/CO₂) according to Table 13. Other parameters, such as primary Pₐ, secondary Pₐ, overall Pₐ, and overall S.R. were all identical when doing the comparison. Although the secondary
Figure 62. The measured mean standoff distance vs. predicted diffusion time to reach ignition point. This figure represents the conditions in Test 6.3 (see Table 13). Data shows the trend of diffusion controlling on the turbulent diffusion coaxial coal jet ignition and flame stability.

stream momentum of the latter is 20% higher than the former, the results still suggest that under similar mixing and burner operating conditions, the flame stability quantified by the standoff distance is majorly dependent on the diffusion process of O$_2$ to the particle surface, which is the slowest and most controlling mechanism compared with turbulent mixing and reactions.

Although Figure 62 shows the similar diffusion controlling mechanism, it also shows that the flame stability is sensitive to the secondary P$_{O_2}$. Figure 63 shows that the results of Test 6.3 are off the track compared with the ones of Test 6.1B and 6.4MM. This is due to the different burner operating parameters, such as the turbulent mixing (secondary momentum), the entrained enthalpy from the secondary stream to the
Figure 63. Data correlation and comparison between Figure 61 and Figure 62

transport coal jet, and the reaction kinetics (overall S.R.). Due to the internal recirculation in the near burner region and the elevated overall $P_{O_2}$, the local $O_2$ concentration of the coal jet is higher in Figure 62 than the one in Figure 61. It is difficult to extract the effect of a diffusion mechanism with other mechanisms varying, as we have discussed in Section 6.3. However, the subsequent effect of local $O_2$ concentration due to the internal recirculation may control the boundary conditions in the data correlating model.

In reality, the problem is very complicated. Firstly, CO$_2$ surrounding the char particles is a reactant in the following char gasification reaction, $CO_2 + C \rightarrow 2CO$, which can affect the volatile yield and the intrinsic reactivity of residual char [33]. Secondly, there are heat transfer and heterogeneous reactions going on simultaneously together with molecular diffusion as well as the convection fluxes due to buoyancy, natural convection, or forced convection. Thirdly, the coal particle surface is not smooth but with a porous
structure, which has a local effect to the reactions. Lastly, the coal particles have a swelling behavior and the whole process is very dynamic, especially in the turbulent environment.

The following are the major problems of the current models. At the surface of a carbon particle, carbon can be oxidized directly in two different reactions:

\[ C (s) + O_2 \rightarrow CO_2, \] (I)

\[ C (s) + O_2 \rightarrow 2CO. \] (II)

The CO formed in the second reaction can be further oxidized to CO\(_2\) in a homogeneous reaction: \[ CO + \frac{1}{2} O_2 \rightarrow CO_2. \] (III)

The CO\(_2\) formed in reaction (I) and (III) may be reduced at the surface of the solid carbon: \[ CO_2 + C(s) \rightarrow 2CO. \] (IV)

Most scientists using the single-film model (Nusselt [137], Essenhigh [15], and Field et al. [35]) totally ignored the homogeneous reaction (III). Those who are using the double-film model (Burker and Schuman [138], and Spalding et al. [139]) assumed the oxidation rate of CO in the gas phase and all the surface reactions are infinitely fast, while the truth is that the rate of reduction of CO\(_2\) at carbon’s surface was quite limited and lower, by at least two or three orders of magnitude, than the rate of carbon oxidation by O\(_2\) or the rate of diffusion of O\(_2\) to the particle’s surface.

Therefore, understanding the O\(_2\) diffusion rate together with detailed reaction kinetics under different environments is very important in uncovering the dominating mechanism during coal particle combustion.

Zhang’s Moving Flame Front (MFF) model, which takes into account the effect of CO oxidizing in the boundary layer around the particle, better considers the above concern. They found that at a fixed gas temperature, after the carbon particle has ignited,
increasing $P_{O_2}$ leads to a larger total rate of reaction. There is a transition of the system to diffusion control and the outward motion of the CO flame front until it is fully detached from the particle’s boundary layer [38-40]. This result also agreed with Young and Niksa’s hypothesis that CO and CO2 are formed simultaneously by reactions (I) and (II) [140], and the results deduced from measurements of the particle temperature that: (1) CO2 formation is preferred at low temperatures (<1100 K) or low oxygen partial pressure (<0.007 MPa), and (2) CO formation is preferred at high temperatures (>1600 K) or high oxygen partial pressure (>0.012 MPa).

Others, such as Hu and Zeng et al., provided the proof from their experiments that the longer ignition delay in CO2 than in N2 is due to the reduced oxygen diffusion to the particle surface [33, 97]. Murphy and Shaddix found that at high temperatures (1300 K - 1800 K), which are typical flame temperatures, the char burnout process is more O2 diffusion-controlled than other mechanisms [136]. Although scientists have realized the importance of the diffusion rate of O2 under oxy-firing conditions, the corresponding measurements and models are still inadequate to quantify this effect, especially since detailed kinetics models are still being improved. Therefore, this data correlation has revealed that the ignition behavior is O2 diffusion-controlled even in a turbulent coal flame and it also shows that the remaining challenges need to be solved with further developments of both detailed kinetics models and experimental measurements.

7.5 Scaling Analysis of the OFC Furnace

Since this research focuses on interactions between known coal ignition chemistry mechanisms and known turbulent two-phase jet flow characteristics and attempts to weave connections between the two, it is of interest to understand the coupling effect
between turbulent mixing and coal combustion reactions and to find out the controlling mechanism. And, as the unsolved question of comparing the effects of different mechanisms in Section 6.3 and 7.4, it is meaningful to understand which physical or chemical mechanism is more important on ignition and flame stability, although during the experiments, the fluid mechanics were kept as simple as possible by keeping either velocity or momentum constant. However, in Section 7.4, when different data were attempted to be correlated to investigate the effect of molecular diffusion, the different conditions could not be neglected because the operating parameters were changed. In other words, turbulent mixing still strongly affected the flame stability together with other burner operating parameters such as \( P_{O_2} \), secondary preheat temperature, and wall temperature, etc. There is a large range of time and length scales of turbulent fluctuations in this combustor. Therefore, to scale the turbulent effects on pulverized coal combustion processes and the controlling mechanisms, the characteristic time/length scales for the major processes should be estimated.

7.5.1 Turbulent Length and Time Scales

Wu et al. [61] summarized the three scales in turbulence [141, 142], which can be identified by the statistics information of the turbulent flow, as shown in Table 23.

The integral scales characterized the large eddies in the flow, which strongly depend on geometry and initial conditions. The integral scales of turbulence eddies have a strong effect on the macro-scale flow pattern. Kolmogorov scale determines the smallest scale found in the turbulent flow. In this scale, inertia and viscous forces balance and molecular diffusion occurs as well as chemical reaction. Taylor micro-scale is often
Table 23. Length and Time Scales of Different Eddies and Reynolds Number Averaging Turbulence Information [61]: \( k \) is turbulent kinetic energy, \( \nu \) is kinematic viscosity of the turbulent flow, \( \varepsilon \) is the turbulent dissipation rate.

<table>
<thead>
<tr>
<th></th>
<th>Integrate scale</th>
<th>Taylor scale</th>
<th>Kolmogorov scale</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length scale</td>
<td>( L_L = k^{3/2}/\varepsilon )</td>
<td>( L_\lambda = (10k\nu/\varepsilon)^{1/2} )</td>
<td>( L_\eta = (\nu^2/\varepsilon)^{1/4} )</td>
</tr>
<tr>
<td>Time Scale</td>
<td>( \tau_L = k/\varepsilon )</td>
<td>( \tau_\lambda = (15\nu/\varepsilon)^{1/2} )</td>
<td>( \tau_\eta = (\nu/\varepsilon)^{1/2} )</td>
</tr>
<tr>
<td>( Re )</td>
<td>( Re_L = k^2/\nu \varepsilon )</td>
<td>( Re_\lambda = k/(3\nu \varepsilon/20)^{1/2} )</td>
<td>( Re_\eta = 1 )</td>
</tr>
</tbody>
</table>

used to represent the magnitude or intensity of the turbulence [61]. The task here is to find which reactions are strongly coupled with the turbulent mixing process.

The turbulent time/length scales are acquired through a 3D numerical simulation with the Reynolds-Averaged Navier-Stokes (RANS) method in FLUENT, as discussed below.

In this simulation, a nonuniform mesh is generated according to the burner and furnace geometry (locally refined in the near burner zone, total number of cells is around 93,000). Model predictions are obtained by solving the time-average conservation equations for the gas and coal particle phases. An Eulerian approach is used for the gas phase while the particle phase is treated in a Lagrangian manner. Coal particle distribution is assumed. The standard \( \kappa - \varepsilon \) method is applied for turbulent fluid flow calculations. Devolatilization is simulated by a first order single reaction model. Volatile combustion is assumed to be controlled by the mixing rate of reactants by using the EBU (Eddy Break-Up) model, instead of a two stream Pre-PDF model. Char burning is governed by chemical kinetic rate and the external diffusion rate of oxygen to the char surface.
The case chosen is the primary P_02 of 20.9% case in Test 6.1B (see Table 13). Although RANS model does not calculate the large eddies in the turbulence, it was still applied to help estimate the magnitude of the time/length scale. The magnitudes of the turbulence scales in the near burner flame region are estimated as: large eddy length scale $10^{-3} – 10^{-2}$ m, Kolmogorov length scale $10^{-4}$ m, large eddy time scale $10^{-3} – 10^{-2}$ s, and Kolmogorov time scale $10^{-4}$ s.

7.5.2 Characteristic Time Scales of Homogeneous Reactions

Homogeneous reactions are usually very complex for pulverized coal combustion. Here only several global reactions are considered when only considering main species. An example of these global reactions and the corresponding parameters can be found in Table 24 (Reference [61]).

The kinetic rates $k$ is given by the Arrhenius equation: $k = A \exp\left(-\frac{E}{RT}\right)$.

At a constant temperature, the characteristic time scale $\tau_h$ for homogeneous reaction is defined as the period that the reactant concentration drops to $1/e$ of its original value. The equation can be written as:

$$\tau_h = \left[A \rho Y_R^n \exp\left(-\frac{E}{RT}\right)\right] \quad \text{(equation 7-6)}$$

where $\rho$ is the gas density, $Y_R$ is the mass fraction of the $R^{th}$ reactant, and $n$ is the exponent of the $R^{th}$ reaction, given in Table 24. This equation also shows that the gas temperature has the biggest effect on the time scale of homogeneous reactions [61]. The calculation results show the magnitudes of time scales for these homogeneous reactions.
Table 24. Reaction rates of typical homogeneous reactions and coal devolatilization

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( R_i ) (kmol m(^{-3}) s(^{-1}))</th>
<th>( A )</th>
<th>( E ) (JK(^{-1})mol(^{-1}))</th>
</tr>
</thead>
<tbody>
<tr>
<td>( CO + \frac{1}{2} O_2 \rightarrow CO_2 )</td>
<td>( R = k_{CO}[CO]^{1.5}[O_2]^{0.25} )</td>
<td>3.16E12</td>
<td>1.67E08</td>
</tr>
<tr>
<td>( CH_4 + \frac{1}{2} O_2 \rightarrow CO + 2H_2 )</td>
<td>( R = k_{CH_4}[CH_4]^{0.5}[O_2]^{1.25} )</td>
<td>4.40E11</td>
<td>1.25E08</td>
</tr>
<tr>
<td>Coal devolatilization</td>
<td>( \frac{dm_p}{dt} = -A_e \exp(-E_v/RT_p)(m_p-m_{pc}) )</td>
<td>2.10E07</td>
<td>3.28E07</td>
</tr>
</tbody>
</table>

are \( 10^{-7} – 10^{-6} \) s when the gas temperature is 2300 K. A one-step coal devolatilization model, shown in Table 24, is applied. The time scale is estimated as the order of \( 10^{-5} \) s.

7.5.3 Characteristic Time Scales of Heterogeneous Reactions

The heterogeneous reactions are primarily:

\( C (s) + O_2 \rightarrow CO_2 \) \hspace{1cm} (R1)
\( C (s) + CO_2 \rightarrow 2 CO \) \hspace{1cm} (R2)

The corresponding parameters can be found in Table 25 (Reference [61]).

The final reaction rate is determined by the diffusion process and the intrinsic chemical reaction rate and can be expressed as:

\[
R_i = \frac{R_{i,d}R_{i,k}}{R_{i,d}+R_{i,k}} \quad \text{(equation 7-7)}
\]

Table 25. Reaction rate parameters of typical heterogeneous reactions

<table>
<thead>
<tr>
<th>Reaction</th>
<th>( A ) (kg m(^{-2})s(^{-1})Pa(^{-n}))</th>
<th>( E ) (JK(^{-1})mol(^{-1}))</th>
<th>( n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>( C (s) + O_2 \rightarrow CO_2 )</td>
<td>3.16E12</td>
<td>1.67E08</td>
<td>0.65</td>
</tr>
<tr>
<td>( C (s) + CO_2 \rightarrow 2 CO )</td>
<td>4.40E11</td>
<td>1.25E08</td>
<td>0.6</td>
</tr>
</tbody>
</table>
where $R_i$ is the final reaction rate of the $i^{th}$ reaction, $R_{i,d}$ and $R_{i,k}$ are the bulk diffusion rate and the apparent chemical reaction rate, respectively.

The equation for the bulk diffusion rate is:

$$R_{i,d} = C_i \left( \frac{(T_p + T_g)/2}{d_p} \right)^{3/4} p_i$$  \hspace{1cm} (equation 7-8)

where $C_i$ is the diffusion coefficient of the $i^{th}$ reactant ($C_i = 3 \times 10^{-12}$ sK$^{-0.75}$), $T_p$ and $T_g$ are the particle temperature (K) and bulk gas phase temperature (K), respectively, $d_p$ is the particle diameter (m) and $p_i$ is the partial pressure of the $i^{th}$ reactant (Pa).

The equation for the apparent chemical reaction rate is given by the $n$th empirical reaction model,

$$R_{i,k} = A_i \exp \left( -\frac{E_i}{R T_p} \right) \left( \frac{p_i}{10^5} \right)^n$$  \hspace{1cm} (equation 7-9)

where the pre-exponential factor $A_i$; the activation energy $E$ and $n$ can be found in Table 25.

The heterogeneous reaction time is defined as the period of the reacting carbon mass dropping to $1/e$ of its original one. If assuming constant reactant concentrations, gas temperature, and particle temperature, the characteristic time scale for the $i^{th}$ heterogeneous reaction, $\tau_{c,i}$ is:

$$\tau_{c,i} = \frac{m_p}{(A_p R_i)}$$  \hspace{1cm} (equation 7-10)
where $m_p$ is the char mass in the particle, and $A_p$ is the surface area of the particle.

Wu et al. calculated the characteristic time scale profile of several heterogeneous reactions changing with the gas temperature, as shown in Figure 64. They found that there are two inflections as the temperature changes during the char combustion reaction with $O_2$. The whole reaction rate is limited by chemical kinetics when the temperature is lower than 1200 K, while the diffusion process is limiting the final reaction rate when the gas temperature is higher than 2000 K [61]. For the temperature ranging between 1200 K and 2000 K, the final reaction rate is controlled by both kinetics and the diffusion process [26, 143].

Figure 64. Characteristic time scale profile of several heterogeneous reactions changing with the gas temperature for char particle size of 70 μm. (Wu et al., Reference [61])
7.5.4 Controlling Mechanism in Flame Regions

In the flame region, the typical temperature is about 2300 K. The characteristic time scales of the homogeneous and heterogeneous reactions can be identified by the equations provided in Section 7.5.2 and 7.5.3. The turbulent time/length scale magnitudes are estimated by the FLUENT simulation in Section 7.5.1. Table 26 and Table 27 show the comparisons of time and length scales for different mechanisms in the near burner flame region of the OFC combustor.

In the flame region, the heterogeneous reactions and the large eddies have the same magnitude of time scales. Therefore, there should be a strong coupling effect between the turbulent macro-scale fluctuations and the heterogeneous reactions. The char ignition and burnout should be affected by the large eddies in the flame regions. For the micro-scale flow field, the Kolmogorov time scales are close to the characteristic time scales of devolatilization and the Kolmogorov length scale has a comparable magnitude to the particle size. The fast devolatilization is not affected by the large eddies while the combustion of the volatile could be strongly affected by the micro-scale turbulence fluctuations, which may lead to destroy the diffusion boundary layers surrounding the

Table 26. Comparison of time scales for different mechanisms in the near burner flame region of OFC reactor

<table>
<thead>
<tr>
<th>Mechanisms</th>
<th>magnitude of time scales (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Homogeneous reactions</td>
<td>$10^{-7} - 10^{-6}$</td>
</tr>
<tr>
<td>Devolatilization</td>
<td>$10^{-5}$</td>
</tr>
<tr>
<td>Komogrov turbulence</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Heterogeneous reactions</td>
<td>$10^{-3} - 10^{-2}$</td>
</tr>
<tr>
<td>Large eddies</td>
<td>$10^{-3} - 10^{-2}$</td>
</tr>
<tr>
<td>Particle residence time</td>
<td>$1 - 10$</td>
</tr>
</tbody>
</table>
Table 27. Comparison of length scales for different mechanisms in the near burner flame region of OFC reactor

<table>
<thead>
<tr>
<th>Mechanisms</th>
<th>magnitude of length scales (m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Particle size</td>
<td>$10^{-5} - 10^{-4}$</td>
</tr>
<tr>
<td>Komogrov turbulence</td>
<td>$10^{-4}$</td>
</tr>
<tr>
<td>Large eddies</td>
<td>$10^{-3} - 10^{-2}$</td>
</tr>
<tr>
<td>Burner diameter</td>
<td>$10^{-2}$</td>
</tr>
<tr>
<td>Combustor top section size</td>
<td>$1 - 10$</td>
</tr>
</tbody>
</table>

particle surface. In the flame region, the combustion of volatiles is much faster than any turbulent fluctuations. Therefore, the homogeneous gas-phase is turbulent mixing controlled.

It is also difficult to fit the diffusion time calculated in Section 7.4 in this time scale comparison, because in reality, the primary gas film surrounding the particles can be much thicker than $100 \, \mu m$, which was assumed in the calculation in Section 7.4. However, this scaling analysis may suggest that the answer to the question in Section 6.3 (Which mechanism between secondary momentum and overall S.R. is more important for Test 6.3 on ignition and flame stability?) is that when fixing primary momentum and varying secondary PO$_2$ by increasing the overall S.R., the effect of secondary momentum and overall S.R. may be equally important. There is a strong coupling effect between the turbulent mixing and heterogeneous reactions according to the results in Table 26 and Table 27.

However, during our experiments, it was very difficult to measure the turbulence fluctuations and the mixing process without advanced diagnostics, such as laser diagnostics. The current theoretical analysis, based on a traditional RANS method, has many limitations. For instance, it cannot consider the turbulent effects on particle
heterogeneous reactions and the devolatilization process. Therefore, RANS cannot predict the characteristics of the near burner flame region in a combustion process. The understanding of the coupling effect between the turbulent mixing and the coal combustion chemistry need to be further developed both experimentally and theoretically. Again, this is the reason for this research to investigate the effect of $P_{O_2}$ on the flame stability when maximally simplifying the turbulent mixing by applying the simple coaxial burner design and keeping the fluid mechanics as constant as possible by matching either velocity or momentum.

7.6 Estimation of Local $O_2$ Concentration in the Coaxial Jet Flame

The local time-averaged $O_2$ concentration is very important in understanding the ignition and combustion in the coaxial jet flame because both ignition and the consequent combustion reaction need the oxidant to take place locally. The local $O_2$ concentration can also affect the combustion kinetics rate as discussed earlier. However, due to the difficulty of measuring gas species without disturbing the flame in the near burner region, it is very hard to provide any experimental data on the local specie concentrations by using any probe technique. Therefore, to help understand the internal recirculation zones and the local $O_2$ concentrations inside the combustion chamber, a FLUENT simulation has been carried out to assist in better understanding the data and the burner design. The corresponding simulation setup can be found previously in Section 7.5.

Figure 65 shows the results of this simulation for the case of primary $P_{O_2} = 20.7\%$ and secondary $P_{O_2} = 44.5\%$ in Test 6.1B (see Table 13). The left figure shows the velocity vectors in the top section of the combustor and where the jet flow is hitting the
Figure 65. FLUENT Simulation Results: Left - velocity vectors showing the internal recirculation zones; Right - the local O₂ mole fraction in the near burner region.

wall and then turns in the reverse direction. The biggest internal recirculation zone is almost as big as the top section length scale. The recirculation zones in the near burner region are very important in stabilizing the flame as they constantly heat up the relatively cold fuel-oxidant jet by the hot recirculating flue gas. The right figure shows the local O₂ mole fraction in the near burner region (24” by 24” on the figure). It shows that the O₂ is quickly consumed by traveling a distance of about 8” (20.3 cm). If assuming the jet angle is 10°, the O₂ mole fraction at the jet edge ranges between 0.13 and 0.15 in the near
burner region. This result also helped choose 14.4 vol% $P_{O2}$ as the ignition criterion in Section 7.4 when calculating the time needed to ignite due to diffusion.
8. CONCLUSIONS

Experiments on a 40 kW, well-defined, turbulent diffusion coaxial pulverized coal jet flame successfully allowed the interactions between coal ignition and coaxial flame turbulence to be explored, and the ramifications of these interactions to be delineated, as they affect the stability of practical oxy-coal flames. A methodology of quantifying coal-flame stability has been developed by applying photo-imaging techniques to measure standoff distance. The image processing code successfully ran on the University of Utah high-performance clusters. PDF statistics were applied to quantify the unsteady behavior of turbulent diffusion flame due to the coupling of turbulent mixing and homogeneous and/or heterogeneous reactions. The partial pressure of primary oxygen has a quantifiable, first-order effect on flame stability. Other factors, such as secondary preheat temperature, partial pressure of secondary oxygen, burner dynamics, etc. are other variables that may influence flame stability in the course of oxy-coal retrofit of current utility boilers. A targeted test, comparing different primary transporting media (O₂/CO₂ mixture and O₂/N₂ mixture), provided additional insight into flame stabilization under oxy-coal combustion. A mass transfer model was developed to correlate the predicted ignition time with the measured mean standoff distance. The results showed that ignition of turbulent diffusion pulverized coal jet is controlled by the diffusion of O₂ to the coal particle surface.

The inferred mechanisms can be summarized as follows:
1) The composition of the primary jet fluid is very important in determining coal-jet stability in coaxial turbulent diffusion jet flames. Not only is the concentration of O$_2$ in CO$_2$ important, but also the diluent containing the oxygen (CO$_2$ versus N$_2$). When CO$_2$ is replaced by N$_2$ in the primary jet, the primary jet need not contain O$_2$ to allow stable flames.

2) The composition and temperature of the secondary jet fluid are also extremely important. Flame stabilization is very sensitive to secondary flow temperatures. At higher secondary flow O$_2$ concentrations, coaxial oxy-coal turbulent diffusion flames can be stabilized with zero oxygen in the primary jet, even at the lower preheat values.

These results are consistent with the following physical view of the interactions between turbulent mixing and coal particle ignition mechanisms: Large eddies transport packets of coal particles, and their surrounding primary fluid, into the secondary fluid. The primary oxygen concentration determines the initial concentration of O$_2$ at the particle surface. In order for the coal to ignite, this must be increased to a required ignition level of O$_2$ at the surface through molecular diffusion of oxygen to the particle surface. This molecular diffusion flux through a film of primary fluid is enhanced by a) increases in the concentration of O$_2$ in the secondary fluid, and b) increases in the diffusion coefficient of O$_2$ in the primary fluid (N$_2$ versus CO$_2$). The pioneering work of Sandia group and B&W group showed that differences in molecular diffusion of O$_2$ in N$_2$ and CO$_2$ could account for delayed ignition and diminished char burnout rates in laminar reactor conditions. Our results are consistent with coal ignition mechanisms that depend on molecular diffusion of oxygen and heat from the secondary stream through the primary stream fluid to the particle surface or to a “blob” of combustibles. Such a process would be facilitated by large eddies transporting pockets of coal particles and
their surrounding primary stream fluid into the secondary fluid stream. The present work suggests that these conclusions can be carried through to practical turbulent oxy-coal jets and that they have direct practical relevance.

The experimental results presented here, together with the preliminary uncertainty quantification included in Appendix D, can contribute to subsequent validation of simulations of this oxy-coal combustion configuration, and these simulations can be used for scale up, and prediction of the retrofit behavior of existing units.
9. RECOMMENDATIONS FOR FUTURE WORK

The results of this investigation provide numerous suggestions for future work:

1) Investigation of different coal types

In this study, only a bituminous coal was successfully investigated on the flame stability. Due to the high moisture content in PRB coal, one of the subbituminous coals, a great difficulty was met in the experiment. Due to the safety concern of drying PRB coal, another subbituminous coal, such as Illinois 6, is suggested to be studied in the future.

2) Investigation of oxy-coal combustion with flue gas recirculation

All the results presented in this work are for the once-through O₂/CO₂ mixture as the oxidant. In the future, the recirculated flue gas may have different impacts on the flame stability compared with once-through oxidant. In the short term, a once-through O₂/CO₂/H₂O(g) mixture is suggested to investigate the effect of moisture in the combustion air on flame stability. In the long term, the flue gas recirculation effect needs to be studied.

3) Mechanisms of coal particle ignition/combustion under high temperature in oxy-firing conditions

The mechanisms of a single coal particle ignition/combustion provide the fundamental insights into oxy-coal combustion in real field boilers. The corresponding mechanisms under oxy-firing conditions, such as devolatilization, ignition, kinetics of volatile combustion or char burnout, are still inadequate now. Further investigations of fundamental research are highly appreciated. The diffusion controlled coal particle
ignition/combustion mechanisms are expected to be developed to understand the difference of combustion characteristics between air-firing and oxy-firing conditions.

4) Understanding of the coupling effect of turbulent mixing and combustion chemistry

In this work, due to the concern of disturbing the flame in the near burner region by inserting a probe, the combustion characteristic measurements are quite limited. In the future, more advanced techniques, such as laser diagnostics, are expected to more quantitatively measure the combustion characteristics in the near burner region. For instance, Particle Image Velocimetry (PIV) can be applied to measure the particle velocities and turbulent mixing in a two-phase flow.

5) Model validation and uncertainty quantification

Since this work is also targeted to contribute to the model validation of the ignition submodel in the near burner region, the uncertainty quantification and careful statistical analysis are needed to better process the massive experimental data in the future. A database for model validation purposes should be built to meet this need.

6) Further development of the current methodology

In this work, the methodology developed succeeded in quantifying the flame stability by applying the optical measurement and image processing techniques. Applying this methodology requires the intensive spectral emissions from the soot generated in the flame. For the PRB combustion case, the soot generated in the near burner zone is less than in the Utah Bituminous coal case, and the chemiluminescence measurement of the radicals might be worth a try. The pictures taken in the experiment by a Nikon DSLR camera can be processed using either two-color or three-color pyrometry to quantify the
temperature profiles in the near burner region, which will contribute to better understanding of combustion characteristics in the near burner zone.

7) Investigation of the effect of the wall temperature

Wall temperature is a degree of freedom for the pulverized coal ignition process. In this experiment, wall temperature is accurately controlled by using electrically heated elements. However, due to the temperature limit of the heating elements, there was little flexibility in adjusting this parameter in the experiment. To study the ignition behavior of oxy-coal combustion in higher temperatures, the furnace wall would need to be retrofitted.
APPENDIX A

DISCUSSIONS OF CHEMILUMINESCENCE NO$_x$

MEASUREMENTS

Chemiluminescence is an effective NO$_x$ emission monitoring technique that has been widely applied in stack emissions and ambient air-monitoring instrumentations. The basic chemiluminescence chemistry was delineated in 1967 by Clough et al. [144]

\[
\begin{align*}
\text{NO} + \text{O}_3 & \rightarrow \text{NO}_2^* + \text{O}_2 \quad (1) \\
\text{NO} + \text{O}_3 & \rightarrow \text{NO}_2 + \text{O}_2 \quad (2) \\
\text{NO}_2^* & \rightarrow \text{NO}_2 + h\nu \quad (\sim 600 \text{ to } 3,000 \text{ nm}) \quad (3) \\
\text{M} + \text{NO}_2^* & \rightarrow \text{NO}_2 + \text{M} \quad (4)
\end{align*}
\]

where $h\nu$ = photons and M = any compound.

Equation (1) and (3) describe the technique employed in commercial instrumentation to measure nitrogen oxides. When NO reacts with O$_3$, some electronically-excited NO$_2^*$ molecules are produced (Equation (1)), which then give off energy in the form of light emission with an intensity proportional to the concentration of NO (Equation (3)). Therefore, the emitted radiation is a measure of the concentration of the NO in the reacting sample [145]. In order to measure NO$_2$, NO$_2$ is first converted to NO, after which the converted molecules react with ozone along with the original NO molecules in the sample. This results in a signal that represents the sum of NO and NO$_2$. 
By taking the difference between the converted and nonconverted modes, a measure of the NO₂ concentration is obtained [145].

One challenge, however, is that chemiluminescent analyzers are subject to the quenching phenomenon. Quenching is a chemical reaction happening at the molecular level, whereby light emission, from the reaction used to detect NO, is reduced by collisions with other gas molecules in the sample. Jernigan et al. reported that the increased presence of a gas such as CO₂ will decrease the sensitivity of the analyzer, due to increased collisions with NO. The collisions of CO₂ with NO will result in less light emitted than if CO₂ were not present and the N₂ and NO collisions will inhibit the light emission less than CO₂ and NO. In other words, N₂ has less quenching tendencies than CO₂. Therefore, under oxy-coal combustion conditions, the quenching effect of CO₂ should be considered.

Properly selecting the calibration gas (cal-gas) is the key to NOₓ chemiluminescence measurement. Under air-firing or oxy-enriched (adding O₂ to air) conditions, the standard gas applied for calibration is a mixture of NO/NO₂/N₂ (denoted by A), in which NO is 826 ppm and NOₓ is 1091 ppm. While under oxy-firing conditions, the standard gas applied is a mixture of NO/CO₂ (denoted by O), in which NO is 956 ppm.

A simple method was developed to correct the NOₓ data if the wrong cal-gas were selected. With two kinds of standard gases A and O, the correction factor can be found by using one as the cal-gas and the other as the sample gas, as shown in Table 28.

The correction factor above is calculated by using this equation:

\[
\text{Correction factor} = \frac{\text{correct NO}_x \text{ concentration}}{\text{measured NO}_x \text{ concentration}}.
\]

Note: the Horiba NOₓ analyzer is only functional in measuring NO.
Table 28. Table of correction factors in NO\textsubscript{x} chemiluminescent measurements if the wrong cal-gas is applied.

<table>
<thead>
<tr>
<th>Cal-gas selected as flue gas</th>
<th>Correct NO/NO\textsubscript{x} (ppm)</th>
<th>Thermal Env. NO\textsubscript{x} Analyzer</th>
<th>Horiba NO\textsubscript{x} Analyzer</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Measured NO\textsubscript{x} (ppm)</td>
<td>Correction factor</td>
<td>Measured NO\textsubscript{x} (ppm)</td>
</tr>
<tr>
<td>A(NO/NO\textsubscript{2}/N\textsubscript{2})</td>
<td>826/1091</td>
<td>1036</td>
<td>1.053089</td>
</tr>
<tr>
<td>O (NO/CO\textsubscript{2})</td>
<td>956</td>
<td>1003</td>
<td>0.953141</td>
</tr>
<tr>
<td>Product of two correction factors (should be 1)</td>
<td></td>
<td>1.003742</td>
<td></td>
</tr>
</tbody>
</table>
APPENDIX B

SUMMARY OF IMAGE PROCESSING

The summary of image processing includes camera non-uniformity evaluation, methodologies, and parallel computing operation procedures.

1. Camera Background Analysis

To study the effect of the potential nonuniformity of the camera sensor on our image processing method, a set of white-background images and a set of black-background images were captured. The images with a white background were taken using a white poster board in the bright sunlight (using the following setup: 30 fps, 0 gain, exposure time of 4 ms, and aperture setting 6). The black background images were taken with the cap on the lens. The image-processing results (i.e., standoff distance) were compared for the background corrected and uncorrected images.

Black Correction: First, a histogram was created of the black background image grayscale pixel values, which range from 0 to 255 (Figure 66). The average matrix was calculated from multiple black background images (100 images) with the cap over the lens. For each flame image, the average black background matrix was subtracted from the flame image matrix, and the standoff distance was determined.
White Correction: First, a histogram was created of the white background image grayscale pixel values (Figure 67). Each grayscale white background image has a matrix of pixel values ranging from 0 to 255. The average matrix was calculated from white images (400 images) for correction. Each flame image is corrected by multiplying the image matrix by the average white-background matrix and dividing by 255.

Combined Correction: We tested 500 attached images, and 2 x 500 detached images. Each flame image was first corrected for the white background. The black background was then subtracted from the white-corrected images.

The maximum difference in standoff distance (background corrected vs. not corrected) for any individual attached flame was approximately 0.2% (see Table 29). In the detached case, the largest percent difference for an individual image was approximately 3.5%. The average percent difference was less than 1%. This corresponded

![Figure 66. Histogram of black image grayscale pixel values](image-url)
Figure 67. Histogram of white image grayscale pixel values

to an approximate change of 10 pixels, but did not contribute to a large change in standoff distance.

2. Pixel to Centimeter Conversion Sensitivity

We investigated the sensitivity of the image processing results (i.e., standoff distance) to the pixel to centimeter conversion factors. The standard image processing method used the known distance of the window break (shown in Figure 68) and the pixel distance measured using the Matlab® imtool function.

The standard standoff distance measurements were compared to those using a hot pipe of a known diameter to determine the pixel to centimeter conversion. The width of the hot pipe was measured with calipers, and a value of the pixel to centimeter was calculated.
Table 29. Sample calculated values

<table>
<thead>
<tr>
<th>Attached Data Ave</th>
<th>Error 0.000113</th>
<th>Detached Ave</th>
<th>Error 0.0009189</th>
</tr>
</thead>
<tbody>
<tr>
<td>10/13 MV PO2=0.207</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Original Black White Combined Correction Combined Correction</td>
<td>Original Black White Combined Correction Combined Correction</td>
<td></td>
<td></td>
</tr>
<tr>
<td>11.05 11.05</td>
<td>11.05</td>
<td>11.05</td>
<td>0</td>
</tr>
<tr>
<td>11.025 11.03</td>
<td>11.03</td>
<td>11.025</td>
<td>0</td>
</tr>
<tr>
<td>11.025 11.03</td>
<td>11.05</td>
<td>11.05</td>
<td>0.002268</td>
</tr>
<tr>
<td>11.05 11.05</td>
<td>11.05</td>
<td>11.05</td>
<td>0</td>
</tr>
<tr>
<td>11.025 11.03</td>
<td>11.03</td>
<td>11.025</td>
<td>0</td>
</tr>
<tr>
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<td>11.025 11.03</td>
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<td>11</td>
<td>11</td>
<td>11</td>
<td>11</td>
</tr>
</tbody>
</table>

Figure 68: Image of window break
To check the sensitivity of the pixel to centimeter conversion, we collected 5 images from 10 different conditions and measured the distance along the window break (in pixels) at different locations. To obtain the pixel to centimeter conversion factor, the pixel length was divided by 6.5 centimeters, the measured length of the window break.

A difference of approximately ±5 pixels was identified depending on where the window break was measured. This leads to an approximately ±1% error in standoff distance due to pixel to cm conversion.

3. Image Processing Procedure

A.) Convert to Grayscale/ Separate Images

1) Make sure the crop size cuts the image at the window break. Do not crop the sides of the images. The crop size of the image can be checked by using the `imcrop` function in Matlab. Copy the value of rect from line 17 into the command window of Matlab. Read image using the `imread` function. Enter `imcrop(I,rect)` into the Matlab command line to check the image crop. Change the value of the height of image in rect if needed (rect = [xmin ymin width height]).

2) Separate and convert images to grayscale by using `seperate_flames2.m`. The following changes are needed:

   Line 6: folder location of images to separate
   Line 10: folder location (Separate each subfolder by comma. Location of images to separate.)
   Line 11: individual file names
   Line 64: name of images with flame (ex: flame_conditions_)
   Line 67: destination of the location of the images with flame
Line 69: name of images with no flame (ex: noflame_conditions_)

Line 71: destination of the location of the images with no flame

Try an initial guess of the pixel value (Pix_AVG) of about 60 on line 63 and 68. With higher Pix_AVG values, more images will be identified as no flame.

3) Check images to make sure separation of images is correct. Check removed image files for images with flames that may have been separated into the no-flame folder.

4) If there are too many dim images in the flame folder or missed images in the no-flame folder, increase Pix_AVG on lines 63 and 68 and rerun. Remember to delete files when you rerun.

B.) If using Desktop (Always check a batch prior to running on clusters or use if small number of images.)

1) Copy images into ‘image_test’ folder (create folder if not in directory) located in the Matlab directory.

2) Run new_oxy_kk2.m

3) Check images to make sure the code is finding the correct edges of the flame. Lines 68 and 110 display images as they are run through the code (figure, imshow()). Lines 68 and 110 may be commented out if images look correct.

4) Script writes to Average_intensity_envelope.txt in the output folder located in the Matlab directory.

5) Open the file named Average_intensity_envelope.txt in Excel and check data. When opening file, use delineate and separate by comma. Check a few images by manually using imtool to see if standoff distance in pixels agrees. To check with imtool, open image through the imtool function in Matlab. Use ruler tool to measure distance to the top edge of the flame.
6) If you are going to use the data, resave the data from Average_intensity_envelope.txt to a new filename. Each time you rerun new_oxy_kk2.m, it will overwrite the text file.

C.) If using CHPC Clusters

1) Prior to moving images, run small sample (~50 images) on desktop computer using the method above to make sure images run correctly.

2) Copy the folder of images (grayscale) to network drive. (Z:\) The network drive is also called the home directory in the clusters.

3) Access clusters through Cygwin from desktop. This is where to log into the clusters. Use the following: Login: ssh uNID@clustername.chpc.utah.edu; Password: uNID password.

4) Check/Create .pbs file (ex: ImageProc.pbs) in home directory. See below. May need to update email address and your directory on the scratch directory.

5) Locate the folder of images in the home directory and copy these to the scratch directory (cp –r folder /scratch/uintah/name). Make sure it is located in the same directory as m-file.

6) Check new_oxy_kk2.m using vim command. Line 14 needs the folder name containing the images. Submit job to queue using qsub command from the directory where the pbs file is located. Example: qsub imageProc.pbs.

7) After job has completed, you will receive an e-mail if you’ve entered your email address in the pbs file. Check to make sure the code did not have any errors by looking at the MatlabOutput file. If no errors were found, locate Average_intensity_envelope.txt file in the output folder in the scratch directory. Copy the
txt file from the scratch directory to the home directory by using the text command (cp –r Average_intensity_envelope.txt ~/)

8) Open file in Excel and check data (as in section B5).

9) The scratch directory should only have temporary files. They need to be removed once the job is complete or the admin may send a message.

*Note: can also use the built-in Matlab to run a set of images. This is faster than running on the desktop. Type in Matlab –r -nodisplay.

**The scratch directory is a temporary directory where the files are run on the clusters. The home directory is on the network directory and may be accessed through the desktop. The files need to be transferred between the home directory and the scratch directory. The home directory is designated by ~/. The scratch directory is /scratch/uintah/name.
APPENDIX C

INDIVIDUAL PDF PROFILES FOR ALL THE
REPLICATES IN CHAPTER 4

1) Test 6.1 A

Primary $P_{O_2} = 0$
Probability Density Function 05/15/2009 Primary PO2=0%, Overall PO2=40%, Preheat T=489 K

Probability Density Function 05/20/2009 Primary PO2=0%, Overall PO2=40%, Preheat T=489 K
Primary $P_{O2} = 0.054$
Probability Density Function 05/20/2009 Primary PO2=0.054, Overall PO2=40%, Preheat T=489 K

Probability Density Function 05/21/2009 Primary PO2=0.054, Overall PO2=40%, Preheat T=489 K
Primary \( P_{O_2} = 0.099 \)
Probability Density Function 05/15/2009 Primary PO2=0.099, Overall PO2=40%, Preheat T=489 K

Probability Density Function 05/20/2009 Primary PO2=0.099%, Secondary PO2=40%, Preheat T=489 K
Primary $P_{O_2} = 0.144$
Probability Density Function 05/20/2009 Primary PO2=0.144%, Secondary PO2=40%, Preheat T=489 K

Probability Density Function 05/21/2009 Primary PO2=0.144%, Secondary PO2=40%, Preheat T=489 K
Primary $P_{O_2} = 0.207$
Probability Density Function 05/20/2009 Primary PO2=0.207, Overall PO2=40%, Preheat T=489 K

Probability Density Function 05/15/2009 Primary PO2=0.207, Overall PO2=40%, Preheat T=489 K
2) Test 6.1 B

Primary $P_{O_2} = 0$
Probability Density Function 06/29/2009 Primary PO2=0, Overall PO2=40%, Preheat T=544 K

Probability Density Function 06/30/2009 Primary PO2=0, Overall PO2=40%, Preheat T=544 K
Probability Density Function 07/01/2009 Primary PO2=0, Overall PO2=40%, Preheat T=544 K

Probability Density Function 07/06/2009 Primary PO2=0, Secondary PO2=40%, Preheat T=544 K
Primary $P_{O_2} = 0.054$
Primary $P_{O_2} = 0.099$
Probability Density Function

06/29/2009 Primary PO2=0.099, Overall PO2=40%, Preheat T=544 K

Probability Density (1/cm)

0 5 10 15 20 25 30 35

Standoff Distance (cm)

0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

Probability Density Function

06/30/2009 Primary PO2=0.099, Overall PO2=40%, Preheat T=544 K

Probability Density (1/cm)

0 5 10 15 20 25 30 35

Standoff Distance (cm)
Primary $P_{O2} = 0.144$
Probability Density Function 06/30/2009 Primary PO2=0.144, Overall PO2=40%, Preheat T=544 K

Probability Density Function 07/01/2009 Primary PO2=0.144, Secondary PO2=40%, Preheat T=544 K
Primary $P_{O_2} = 0.207$
3) Test 6.3

Overall $P_{O2} = 40\%$
Overall PO$_2$ = 41%
Overall $P_{O2} = 42\%$
Overall $P_{O2} = 43\%$
Overall $P_{O_2} = 44\%$
Overall $P_{O2} = 48\%$
4) Test 6.4 MV

Primary PO$_2$ = 0
Primary $P_{O2} = 0.054$
Probability Density Function

10/13/2009 O2/N2 Match Velocity, Primary PO2=0.054, Overall PO2=40%

0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

Standoff Distance (cm)

Probability Density Function

10/14/2009 O2/N2 Match Velocity, Primary PO2=0.054, Overall PO2=40%

0.12
0.11
0.1
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0

Standoff Distance (cm)
Primary $P_{O2} = 0.099$
Primary $P_{O_2} = 0.144$
Probability Density Function 10/13/2009 O2N2 Match Velocity, Primary P02=0.144, Overall PO2=40%

Probability Density Function 10/14/2009 O2N2 Match Velocity, Primary P02=0.144, Overall PO2=40%

Standoff Distance (cm)
Primary $P_{O2} = 0.207$
5) Test 6.4 MM

Primary $P_{O2} = 0$
Primary $P_{O2} = 0.054$
Probability Density Function 10/15/2009 O2N2 Match Momentum, Primary PO2=0.054, Overall PO2=40%

Probability Density Function 10/16/2009 O2N2 Match Momentum, Primary PO2=0.054, Secondary PO2=40%

Primary PO2 = 0.099
Primary $P_{O_2} = 0.144$

\[ \text{Probability Density Function} \]
Primary $P_{O2} = 0.207$
Probability Density Function 10/16/2009 O2:N2 Match Momentum, Primary PO2=0.207, Secondary PO2=40%
APPENDIX D

UNCERTAINTY QUANTIFICATION

The calculated statistics from the PDF data are the mean, variance, skewness, and kurtosis, calculated using Matlab functions and the moment function. In Matlab, these can be calculated by using the “mean,” “var,” “skew,” or “kurt” functions.

The mean is the average, and the variance is a measure of how much the data vary.

The skewness is the measure of asymmetry. A perfectly symmetric distribution will have a skewness value of zero. The more positive the value is, the more spread out to the right it is. The more negative, the more it is spread out to the left.

Kurtosis is a measure of how outlier-prone a distribution is. The kurtosis of the normal distribution is 3. Distributions that are more outlier-prone than the normal distribution have kurtosis greater than 3; distributions that are less outlier-prone have a kurtosis less than 3.

The skewness is also known as the third sample moment and the kurtosis is the fourth sample moment.

The statistics of the distribution were calculated through the use of Matlab functions. These statistical functions were able to calculate the mean, variance, skewness, and kurtosis. The formulas of skewness and kurtosis are:
skewness = \frac{\sum(x - \mu)^3}{n \sigma^3}

kurtosis = \frac{\sum(x - \mu)^4}{n \sigma^4} - 3

where \( \mu \) = the mean of sample, \( \sigma \) = standard deviation of sample, and \( n \) = sample size.

The other method of calculating the moments of the plot is through the use of the moment function. The moment function in Matlab measures the central sample moment and is defined by the following

\[ m_k = \sum (x - \mu)^k \]

where \( m_k \) = the \( k^{th} \) moment, and \( \mu \) = the mean of sample.

The “zeroth” moment is equal to one, the first is equal to zeros, and the second is equal to the variance. The third and fourth central moment are used in calculating the skewness and kurtosis.

The results of uncertainty quantifications can be found in the CD-ROM attached.
APPENDIX E

OFC SAFETY OPERATION PROCEDURES

1) Install the natural gas burner.
2) Connect the natural gas hose and secondary air hose.
3) Hook the peeper (flame detectors) to the burner.
4) Check the cooling tower water level. Make sure that the green light is on. If not, turn on the city water valve to reach the desired water level.
5) Turn on the water pump of the OFC to let cooling water run through. Make sure that there are no hoses connected to the heat exchanger with valves closed and water sealed in the heat exchangers. Otherwise the high temperature and high pressure steam can explode the water hose.
6) Turn on the ID fan to vent the exhaust.
7) Leave primary air (10 lb/hr) running through the primary stream line including the educator to cool down the whole line.
8) Turn on the secondary air.
9) Adjust the furnace pressure to about -0.30 inches water.
10) Turn on the sparker and then the natural gas.
11) If ignited, turn off the sparker and then turn on the peeper chart. If ignition failed, turn off the natural gas immediately and increase the air. Wait for at least 5 minutes to
drain out the remaining unburned natural gas out and then repeat procedure 7) until it succeeds.

12) Adjust the secondary air flow rate and the natural gas flow rate (if needed) to set overall S.R. between 1.3 and 1.5. Adjust the furnace pressure to keep it at -0.30 inches water as needed.

13) Record the natural gas usage according to the meters.

14) Before switching from the natural gas burner to the coal burner, a minimum of 6 hours is needed for the furnace to warm up. Turn on the wall heaters to 1850 °F and wait for half an hour. During this period, the gas analyzers can be calibrated. The hoper of the coal feeder can also be refilled.

15) Leave gas analyzers running at dry air and quickly switch to the coal burners. Turn on the air and the coal feeding, making sure that the coal jet is ignited. Turn on the secondary preheater. Adjust to the correct S.R. (such as 1.15) and the right furnace pressure (about 0 inches water), turn on the gas analyzer and make sure that a mass balance is obtained.

16) Wait for at least one hour to let the furnace reach steady state under air-firing conditions. Then turn off the coal supply and quickly switch to the oxy-firing conditions. Caution: DO NOT turn on the oxygen unless the CO₂ flows are steady and have reached to the required flow rate. Be extremely careful when operating the primary O₂ line to avoid any potential explosion.

17) Check mass balance and wait until the furnace reaches steady state, then start testing. Quartz windows should be cleaned every half an hour.
18) Finish the test and switch from oxy-firing condition to air-firing conditions. Turn off the O_2 and CO_2 tanks. Switch the coal burner to the natural gas burner. Repeat process from procedure 2.
APPENDIX F

CD-ROM OF SUPPLEMENTARY MATERIALS

The CD-ROM attached to this dissertation contains the supplementary materials of Appendix C and D.

1) “Appendix C -03242010_data-PDF Final”
   This folder contains the PDF data for all test conditions, as described in Appendix C.

2) “Appendix D -Statistical Analysis”
   This folder contains the statistical analysis and uncertainty quantifications of the experimental data, as described in Appendix D.

3) Readme.txt
   This text file contains a brief description of the contents included in the CD-ROM. Contacts are also provided for further assistance.
REFERENCES


72. F. El-Mahallawy and A. Abdelhafez, "Mixing and nozzle geometry effects on flame structure and stability," presented at MCS4, Lisbon, Portugal, 2005.


