Full-Scale Demonstration and CFD Model Evaluation of an Oxy-coal Firing System with Undiluted Oxygen and Minimal Flue Gas Recycle

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Abstract

The future use of coal as a fuel for industrial applications depends on economical technologies being made available to capture and store the CO_2 emitted as a product of the combustion process. One such technology is oxy-combustion, which involves burning of the fuel using pure oxygen as the oxidant rather than air. Since heat from combustion does not go toward the heating of nitrogen in the air, flame temperatures with oxy-combustion increase dramatically. First-generation application of the oxy-combustion depends on flue gas recycle (FGR) introduced in or around the burners to modulate flame temperatures to make the technology a retrofit option for existing power generating units. A second generation oxy-combustion technology that uses minimal FGR produces high temperature flames in excess of 4000°F. Application of this technology shows promise for enabling capture, utilization, and sequestration of CO_2. However, a major step in the advancement of the technology and use in retrofit applications is the development of a burner design strategy capable of producing and sustaining the high temperature conditions from oxy-firing of coal while providing protection to burner internals and near-burner surfaces from the high heat fluxes produced.

This paper discusses the full-scale single-burner demonstration of a high temperature oxy-coal firing system patented by Jupiter Oxygen Corporation (JOC). The patented design was achieved through Reaction Engineering International's commercial and government R&D programs involving CFD modeling coupled with multi-scale experiments. CFD model predictions corroborated by experimental data evaluated impacts of burner operation on flame behavior, heat release and heat flux. The paper describes the results of full-scale burner performance testing conducted with a single 60 MMBtu/hr burner under oxy-fired and air-fired conditions. Performance metrics such as flame location/stability, local peak tube/burner temperatures and heat fluxes, carbon conversion, and NOx emissions will be discussed along with comparisons to CFD model simulations of the demonstration's test conditions.

Introduction

High temperature oxy-combustion is an advanced combustion technology that uses minimal FGR in the burner to produce flame temperatures in excess of 4000°F. Application of this technology to steam generation in utility boilers is promising because of the potential for capture, utilization, and sequestration of CO_2. Reaction Engineering International (REI) has led teams of experts across academia and industry to perform multi-scale experiments, coupled with mechanism development and computational fluid dynamics (CFD) modeling, to develop data and tools to characterize and predict flame behavior, heat transfer, ash deposition and ash chemistry during high temperature oxy-coal combustion. These properties must be understood and controlled to enable practical application of oxy-combustion in full-scale systems.

The JOC-patented oxy burner developed under REI's commercial and government R&D programs has been designed to implement the desired high flame temperature with a stable, robust flame with acceptable heat flux and surface temperatures near the burner and throughout the furnace. It is comprised of 4 annular registers surrounding a center igniter as depicted in Figure 1. The burner produces elongated heat release and heat flux distribution, which was targeted for purposes of protecting the furnace from extreme conditions that could compromise the integrity of the equipment. The outermost register allows a small flow of FGR while oxy-firing to provide localized cooling and protection from high incident heat fluxes. This outer register also allows for aerodynamic stabilization during air-firing with the incorporation of swirl vanes.

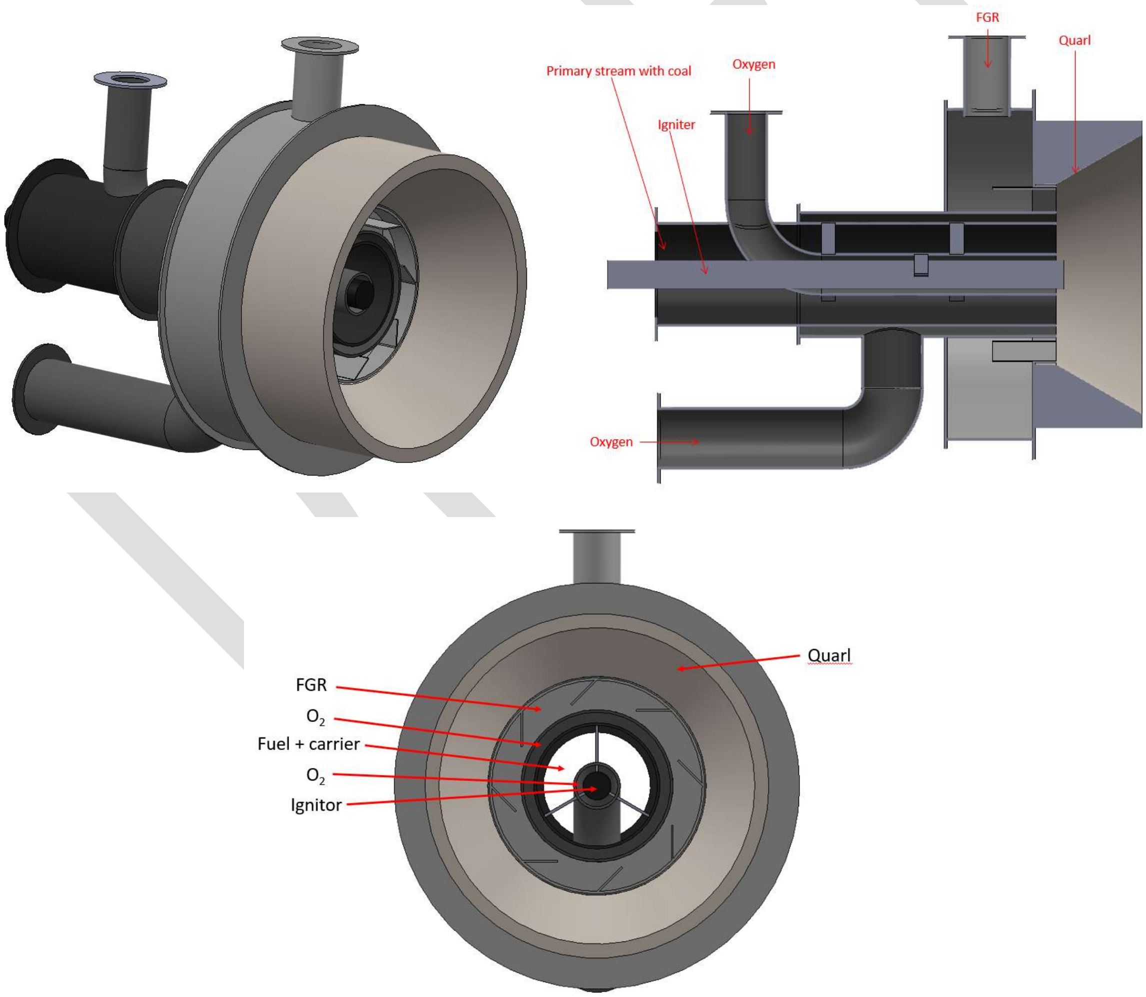

Figure 1. JOC Annular Shroud High-temperature Oxy-burner

The experimental data, oxy-firing system principles and oxy-combustion process mechanisms provided by this work can be used by electric utilities, boiler OEMs, equipment suppliers, design firms, software vendors, consultants, and government agencies to assess the use of high temperature oxy-combustion in current research; evaluate key combustion-related and balance of plant considerations in retrofit applications; and guide the development of new oxy-coal boiler designs.

Experimental Setup

The test campaign discussed in this report, investigating a full-scale single burner, was the next step in development of the JOC high temperature annular shroud burner. The testing was performed with a 60 MMBtu/hr burner firing PRB coal under oxy- and air-firing conditions at the GE Steam Power Inc (GESPI) Industrial Scale Burner Facility (ISBF) located at the Clean Energy Center in Bloomfield, CT. The ISBF is a balanced draft, front wall fired combustion test facility designed to replicate the time, temperature, and stoichiometry (mixing) history of a typical industrial steam generator. GESPI's Pulverizer Development Facility (PDF) was used to pulverize all 700 tons of North Antelope Rochelle Mine (NARM) coal utilized during testing. The furnace walls and heat transfer surfaces of the ISBF are cooled by a surrounding, atmospheric pressure, water jacket. Selective refractory lining of the inside furnace walls, and control over the fuel firing rate are utilized to maintain an appropriate furnace gas time-temperature history as compared to that of the commercial furnace or process being evaluated. The ISBF is instrumented to measure essentially all process flows, temperatures, and pressures, a total of ~440 measurements. Critical furnace operation and control information are measured, metered, and recorded by a state-of-the-art data acquisition and control system. In addition to the continuously logged data, probing and sampling is conducted at selected test conditions and furnace locations. The facility is equipped with a Durag high resolution thermal imaging camera to take visual images and videos as well as thermal images of the burner flame. Figure 2 shows a process schematic of the ISBF and its supporting equipment configured for the JOC oxy-combustion burner testing. Figure 3 shows the fabricated burner installed in the ISBF.

Two, one-week, 24x7 test campaigns were conducted for the JOC Oxy-combustion burner testing. The test program was designed to verify key features of the JOC burner design:

- High-temperature, stable, robust flame
- High combustion efficiency
- Acceptable heat flux and surface temperatures near the burner and throughout the furnace.

The range of parameters tested is highlighted in Table 1. Parameter variation for individual tests under air- and oxy-firing included load, shroud flow, primary oxygen concentration, air leakage, primary gas to coal ratio, excess oxygen, FGR temperature, burner stoichiometric ratio (air only), swirl, and core oxidant distribution.

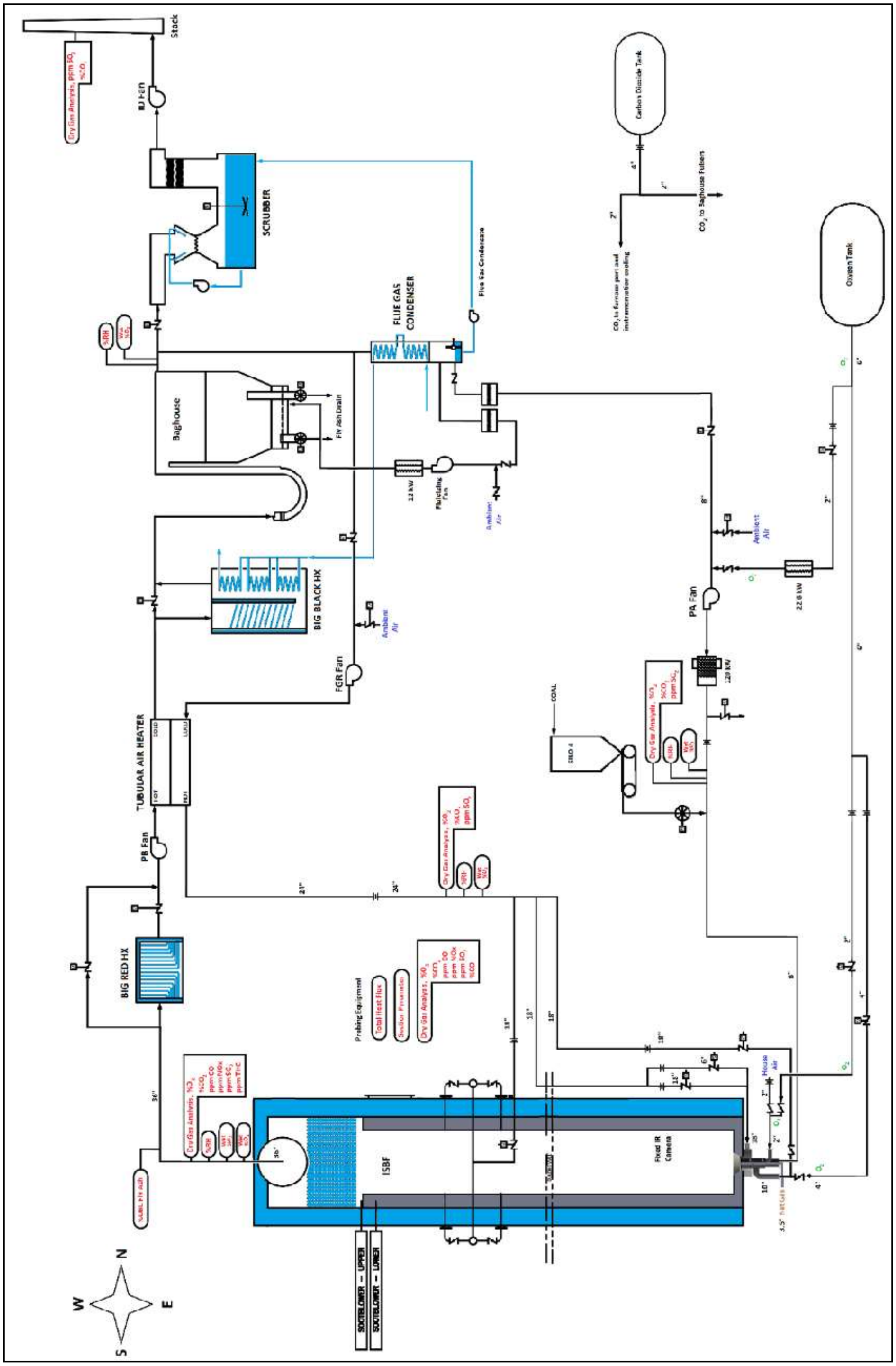

Figure 2. ISBF and Supporting Equipment Process Schematic

Figure 3. JOC burner installed in the ISBF

Table 1. Range of parameters tested

Parameter	Design	Minimum Tested	Maximum Tested
Load (MMBtu/hr)	60	24	59
Shroud FGR flow (lb/hr)	1500	1300	7500
Primary O_2 Conc (vol%, wet)	23.5%	3.4%	23.6%
Leakage (norm vol% of total flow)	~5%	~5%	~8%
Pri Gas / Coal (lb/lb)	1.75	1.69	3.30
Excess O2 (vol%, dry)	~3%	2.2%	5.3%
FGR Temperature (F)	~490	457	537
BSR (air-fired)	1.15	0.78	1.28
Swirl	Oxy: closed Air: open (45 deg from closed)	Oxy: open Air: open	Oxy: closed Air: 25 deg from closed
Core Oxidant	Oxy: ~15% of core+annular Air: ~25% of core+annular	Oxy: 0% Air: 0%	Oxy: 23% Air: 38%

Testing Results

The two-week test campaign was successful with the burner displaying robust performance over test conditions that covered a broad operating range. Under oxy-firing, the flame exhibits clean edges with predominantly axial flow as shown in Figure 4a. Flame initiation begins in the quarl region with strong attachment. Under oxy-firing with minimal FGR in the burner, the extremely high temperatures allow for very fast combustion kinetics which stabilize the flame. With air-firing, the flame is still well attached with initiation in the quarl region as shown in Figure 4b. However, the flame is bushier with increased radial mixing. A majority of the air passes through the shroud region with a swirl number of ~1. This helps aerodynamically stabilize the flame, which is necessary in the absence of the extreme flame temperatures seen while oxy-firing with minimal FGR. Under extreme off-design conditions (multiple parameter variation), the oxy-flame showed some stand-off for brief moments as shown in Figure 5. This behavior is an effect of delayed fuel-oxidant mixing. There was never any danger of losing the flame as the high-temperature kinetics ignite the flame as soon as the mixing is sufficient (whether at the burner front or slightly downstream).

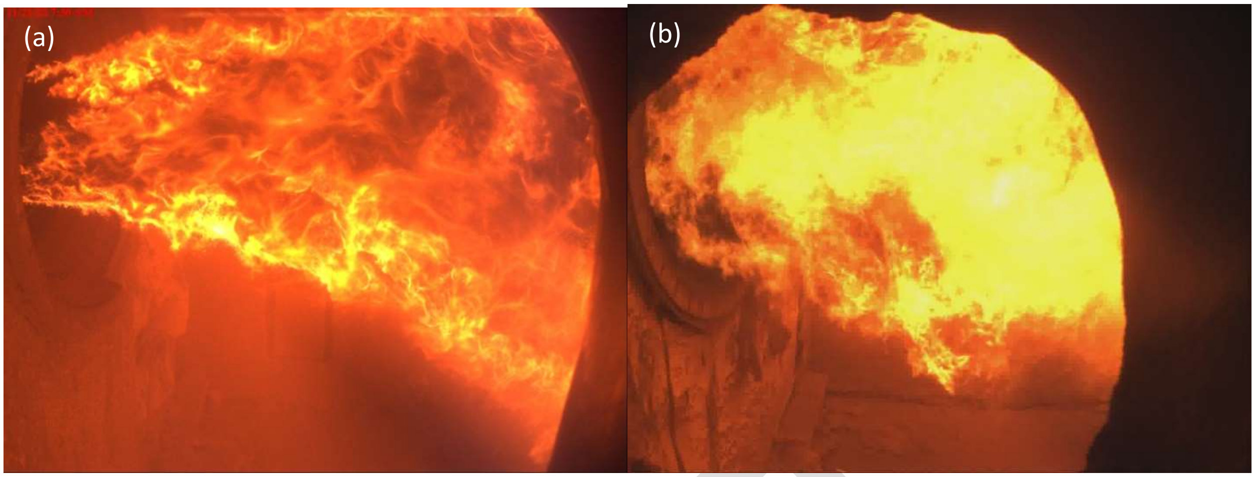

Figure 4. Flame images at design conditions (a) oxy-fired at 59 MMBtu/hr, (b) air-fired at 51 MMBtu/hr

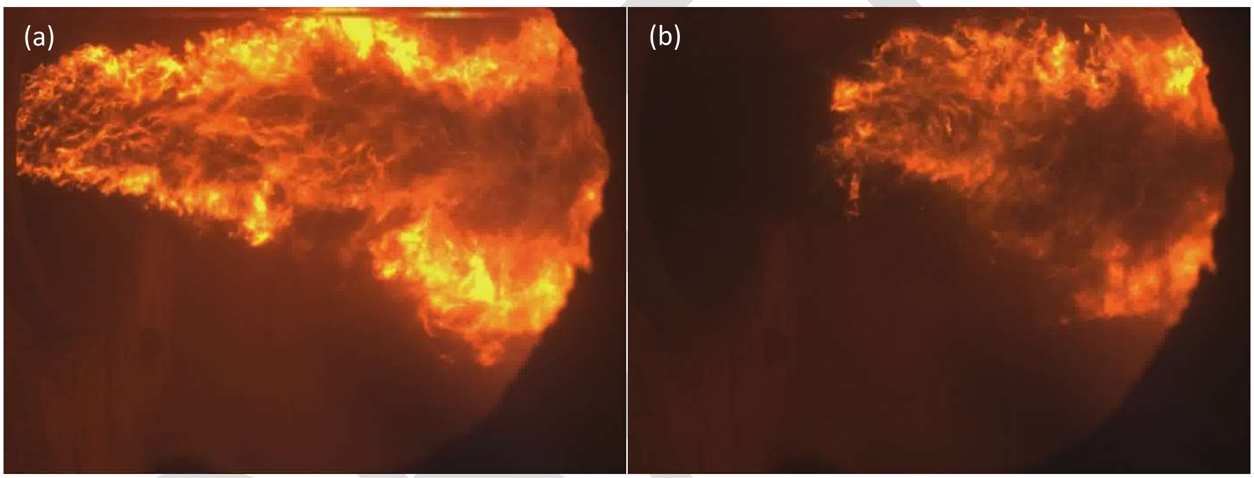

Figure 5. Oxy-fired flame under extreme off-design conditions (48 MMBtu/hr)

Combustion efficiency was high for all tests and burner component temperatures remained low. Unburned carbon in ash was generally less than 1% (Figure 6). Parameter variation did not show any significant impact on UBC under oxy-firing. High combustion efficiency with low unburned carbon is a key characteristic of this high temperature oxy coal technology which has been demonstrated in combustion testing at every scale. Air-firing tended to have higher levels of UBC, as expected, but in the lower range for typical conventional air-fired power boilers. Staged combustion and less swirl tended to increase UBC.

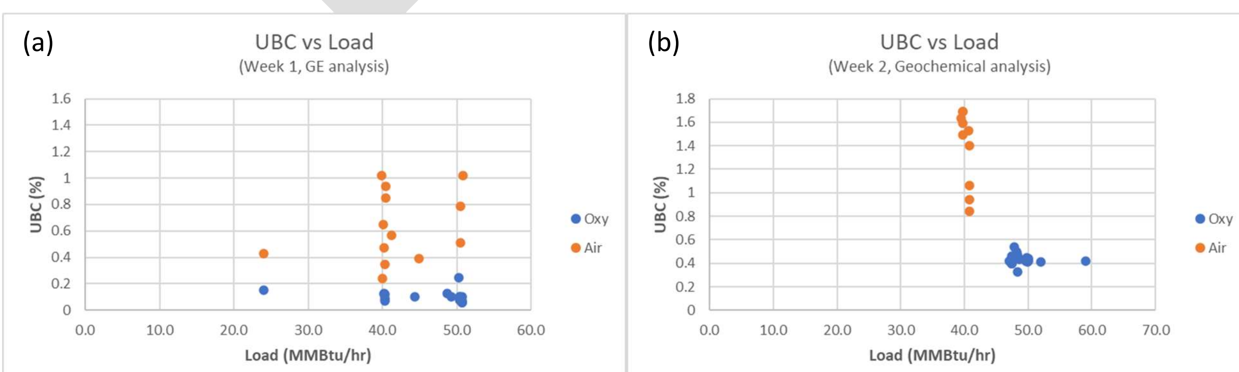

Figure 6. UBC in fly ash as a function of load

CO levels were comparable between air- and oxy-firing. CO levels were managed using excess O_2 throughout the test. NOx concentrations were higher under oxy-firing, as expected, due to higher combustion temperatures. Parameter variation that tends to decrease flame temperature will decrease NOx concentrations, particularly increased shroud flow under oxy-firing. Under air-firing, staging was successful at reducing furnace exit NOx concentrations. Nevertheless, NOx emissions will not generally be a concern with oxy-firing, as nitric acid is condensed and extracted during the cryogenic CO_2 removal process.

At a given firing rate, oxy-firing showed higher gas temperature in the furnace (Figure 7) and increased heat flux (Figure 8). Oxy-firing also tended to show higher burner component temperatures, but values were never higher than acceptable. Parameter variation that tends to decrease flame temperature will also decrease burner component temperatures (increased shroud flow, decreased oxygen concentration in the primary) as shown in Figure 9. Under air-firing, staging caused a decrease in heat flux in the front region of the furnace and an increase after the SOFA ports. With staging, air distribution between the core and annular registers showed an impact on heat flux.

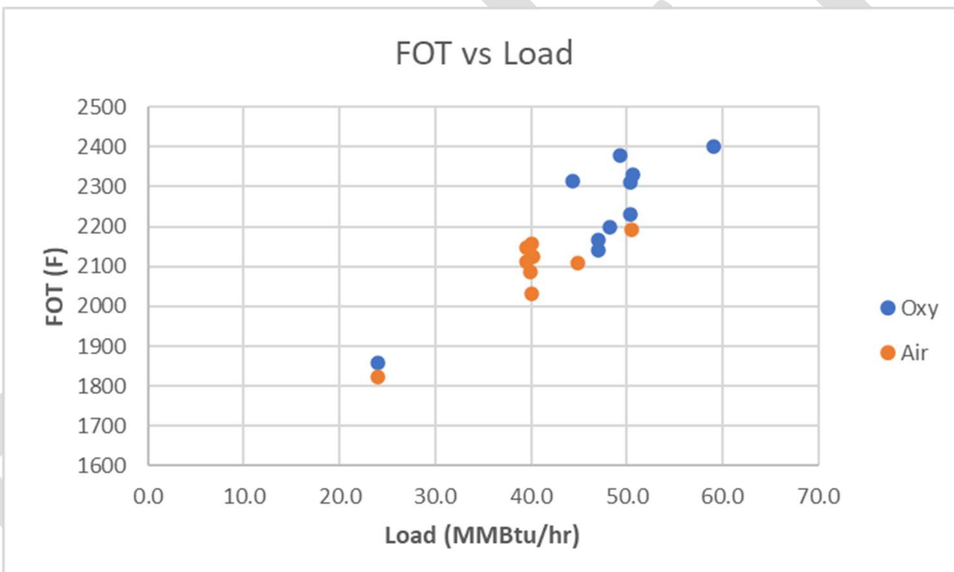

Figure 7. Furnace outlet temperature (FOT) as a function of load

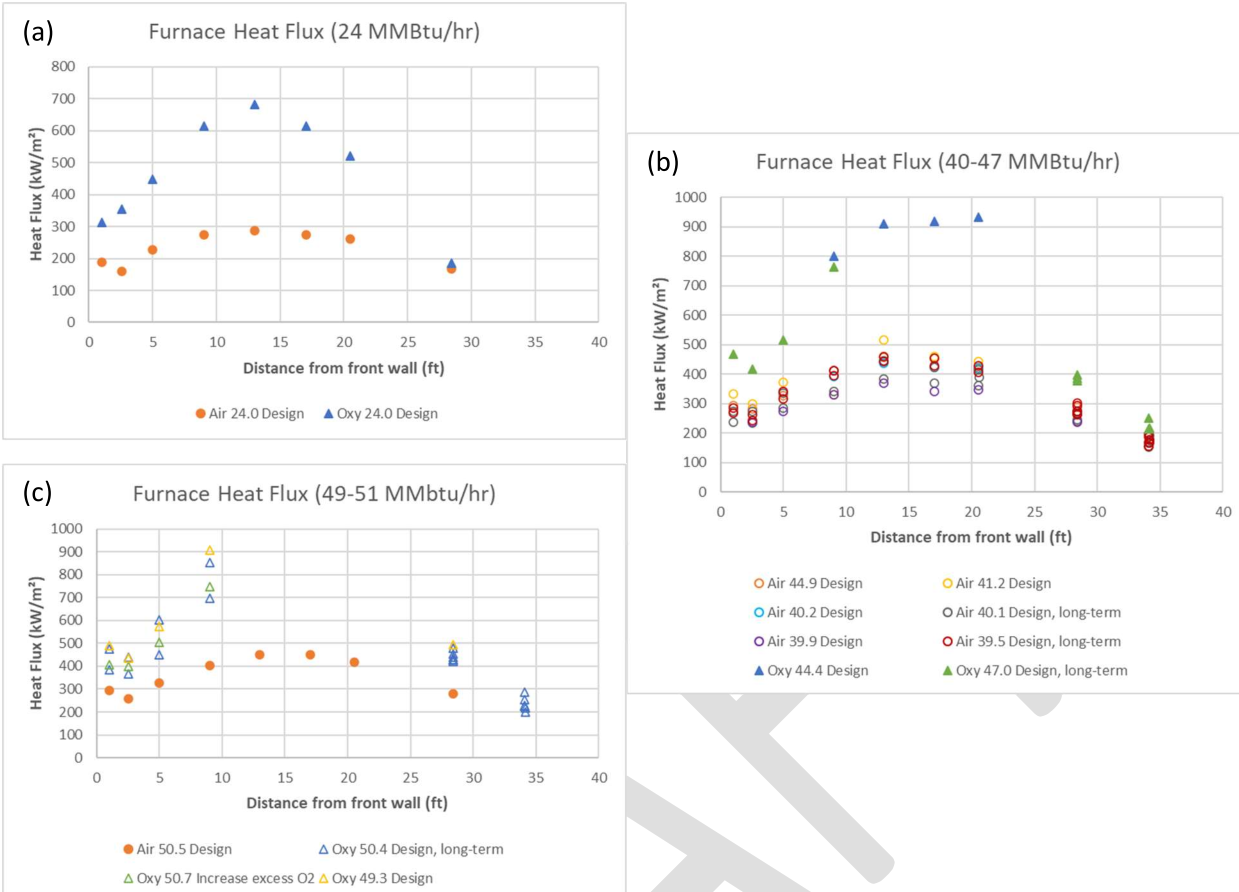

Figure 8. Furnace heat flux comparing air- and oxy-firing under various loads

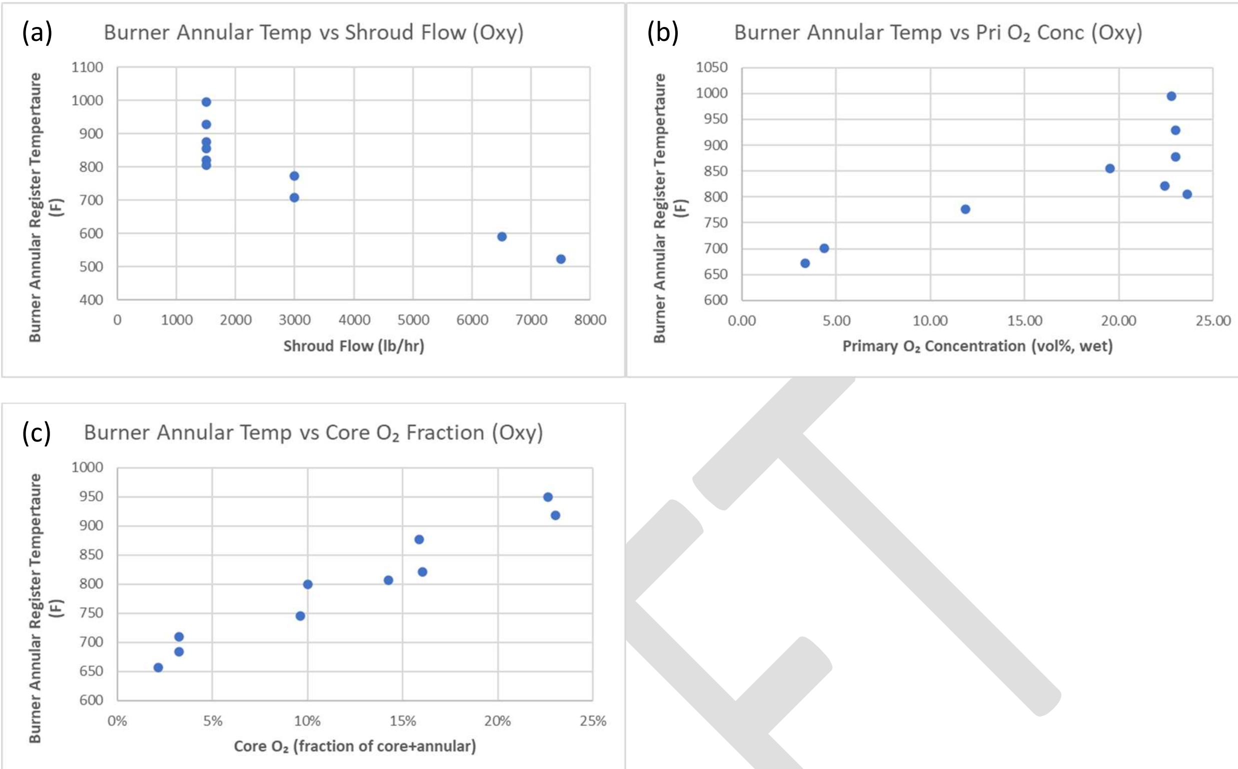

Figure 9. Burner annular register metal temperature as a function of (a) shroud flow, (b) primary oxygen concentration, and (c) fraction of oxygen to the core under oxy-fired conditions

CFD Modeling

Detailed Computational Fluid Dynamics (CFD) modeling has been performed for comparison to test results. Test Operating conditions were used as inputs to the model including coal properties, coal and gas flow rates, stream temperatures and compositions. REI's proprietary CFD code, *GLACIER*, was used for this task. REI's GLACIER model has previously been validated against data at smaller scale under high-temperature oxy-combustion and it has been verified that the model's existing mechanisms can accurately describe the combustion behavior under the test conditions. Comparison to ISBF data collected in this study can further validate the model at a larger scale.

Flame shape predicted by the CFD model as defined by a CO iso-surface at 5000 ppmvw (Figure 10) and gas temperature profile (Figure 11) qualitatively matched the visual flame observed by the camera in the furnace for oxy-firing under design conditions at 59 MMBtu/hr (Figure 12). Some flame stand-off is observed in the model (~1 ft). Model predicted peak gas temperatures occur near the flame initiation plane (peak=4285°F) and temperatures >3500°F persist approximately 1ft past the first level of SOFA. Predicted incident heat flux peaks approximately 17 ft from the front wall (peak=877 kW/m^2). The shape of the heat flux curve as a function of furnace length is consistent with data.

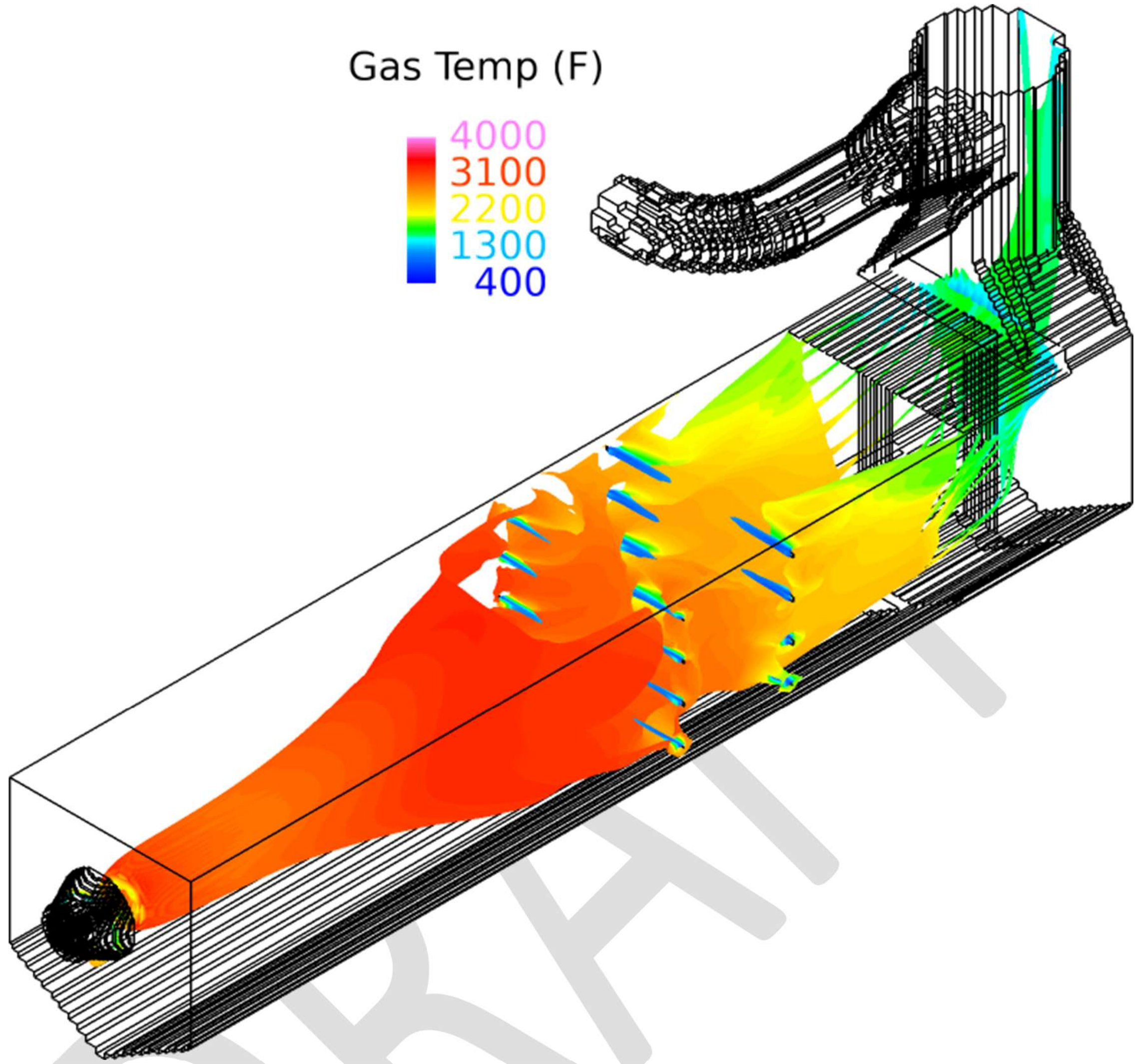

Figure 10. Oxy-fired 59 MMBtu/hr CFD model prediction of flame shape (CO iso-surface at 5000 ppmvw)

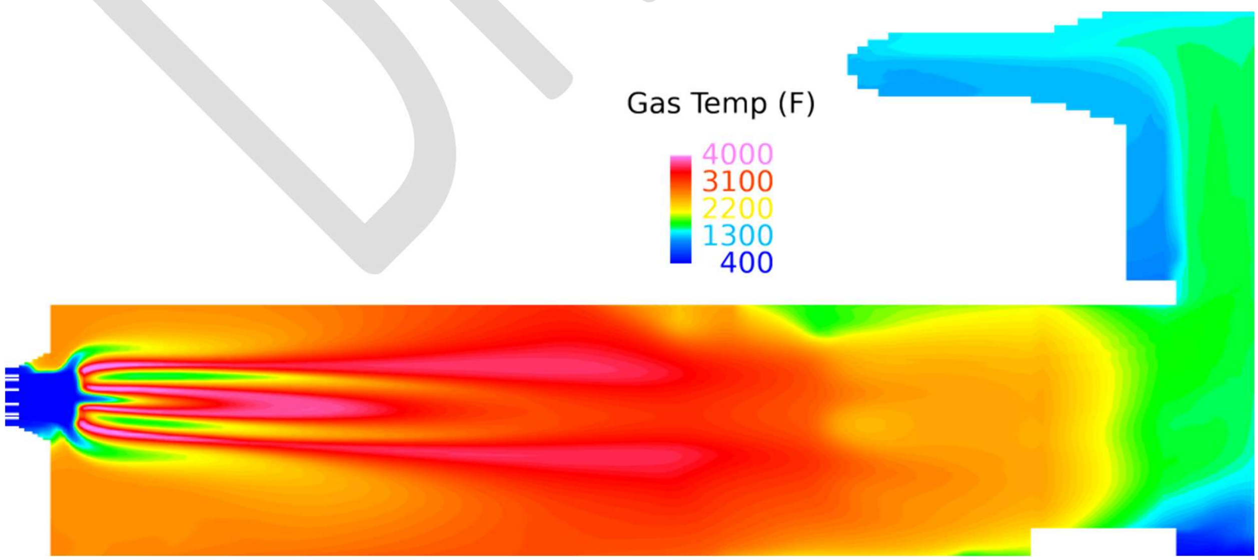

Figure 11. Oxy-fired 59 MMBtu/hr CFD model prediction of gas temperature

Figure 12. Oxy-fired 59 MMBtu/hr camera images

Modeling of a 47 MMBtu/hr oxy-fired test at design conditions showed lower gas temperatures at the screen tubes compared to the test at 59 MMBtu/hr, which is consistent with camera observations. With the decrease in load, trends in furnace stack exit temperature (decrease), O_2 (decrease), CO (increase), and NOx (decrease) were accurately predicted by the CFD model. Less flame stand-off was observed as expected due to lower throat velocities. Predicted peak gas temperature was 4229°F and peak incident heat flux was 769 kW/m^2.

Modeling of an extreme off-design oxy-fired condition at 48 MMBtu/hr showed more flame stand-off (~3 ft) consistent with the camera observation of intermittent flame attachment. The off-design operating conditions for this test (lower oxygen in the primary stream, increased primary gas to coal ratio, and increased shroud FGR flow) are all consistent with a less attached flame and will contribute to decreased flame temperatures resulting in lower incident heat flux. In comparison with the test at 47 MMBtu/hr design conditions, trends in furnace stack exit temperature (similar), O_2 (increase), CO (decrease), and NOx (decrease) were accurately predicted by the CFD model. Predicted peak gas temperature was 3936°F and peak incident heat flux was 604 kW/m^2.

Modeling of air-firing at design conditions at 48 MMBtu/hr (Figure 10 and Figure 11) showed similar flame behavior compared to camera observations (Figure 12). Predicted flame stand-off is ~1 ft. Model predicted peak gas temperature of 3260°F is significantly lower than oxy-firing as is predicted peak incident heat flux of 286 kW/m^2. This air-fired model predicted increased furnace exit CO, decreased furnace exit NOx, and increased UBC in fly ash compared to oxy-firing, consistent with data.

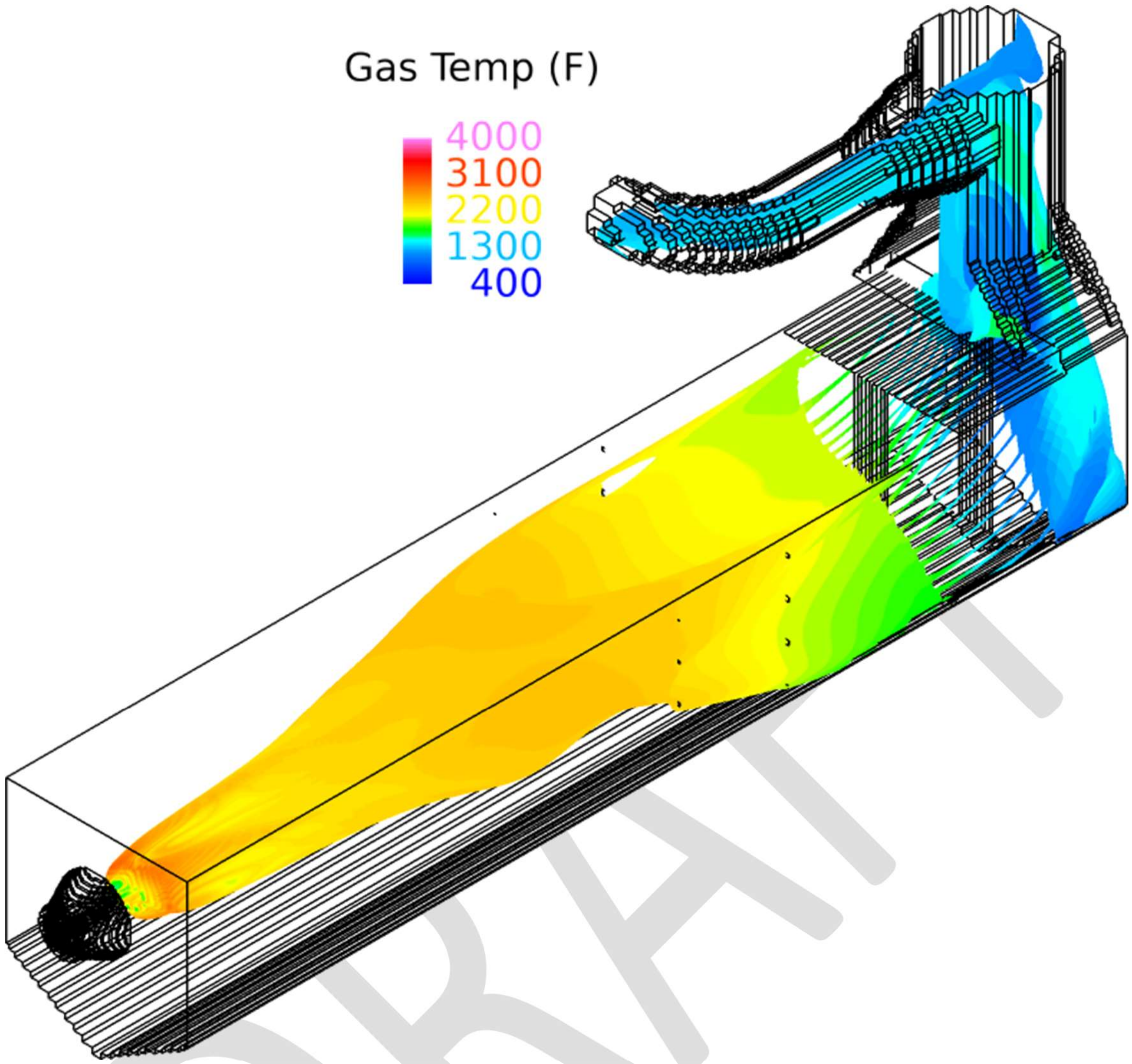

Figure 13. Air-fired 48 MMBtu/hr CFD model prediction of flame shape (CO iso-surface at 5000 ppmvw)

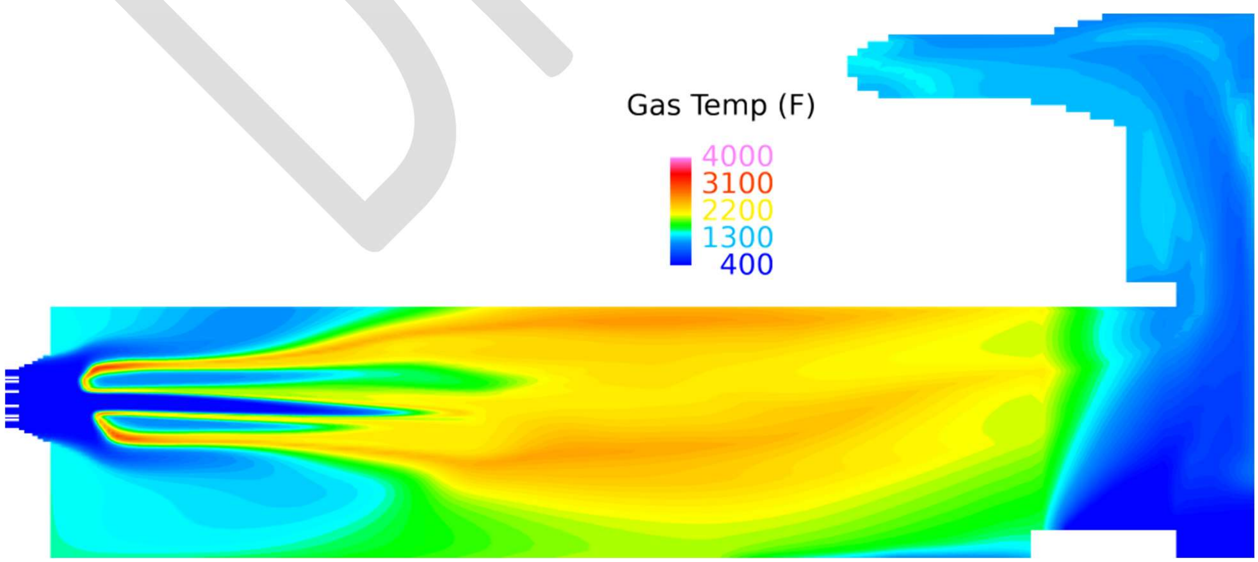

Figure 14. Air-fired 48 MMBtu/hr CFD model prediction of gas temperature

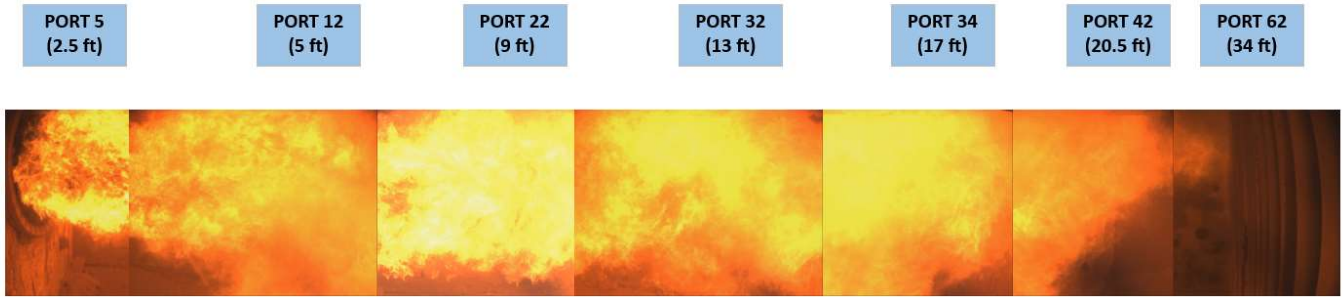

Figure 15. Air-fired 48 MMBtu/hr camera images

Conclusions

The two-week JOC single burner test campaign was successful. All anticipated tests were completed and burner performance was consistent with CFD-based design assessments. The burner produced a stable, well-attached flame for all test conditions, which covered a broad range of operating space and exhibited the burner's robustness. Parameter variation for individual tests under air- and oxy-firing included load, shroud flow, primary oxygen concentration, air leakage, primary gas to coal ratio, excess oxygen, FGR temperature, burner stoichiometric ratio (air only), swirl, and core oxidant distribution. Continuous measurements recorded by the DCS system included gas composition at several locations, temperatures, pressures, and flow rates. In addition, probe measurements of heat flux and furnace outlet temperature were taken. A detailed mapping of gas composition throughout the furnace was completed during long-term testing on both air- and oxy-firing.

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CO levels were comparable between air- and oxy-firing. CO levels were managed using excess O_2 throughout the test. NOx concentrations were higher under oxy-firing, as expected, due to higher combustion temperatures and removal of N_2 diluent. Parameter variation that tends to decrease flame temperature will decrease NOx concentrations, particularly increased shroud flow under oxy-firing.

Under air-firing, staging was successful at reducing furnace exit NOx concentrations. Nevertheless, NOx emissions will not generally be a concern with oxy-firing, as nitric acid is condensed and extracted during the cryogenic CO_2 removal process.

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The test data developed in this program have been used to further validate REI's CFD code *Glacier*. Model predictions agreed well with data for the test conditions modeled (3 oxy-fired cases at two firing rates and one air-fired case). Stable, robust flames were observed in the modeling with very high combustion efficiency. Furnace heat flux increased under oxy-firing, consistent with data.