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Results of initial operation of the Jupiter Oxygen Corporation oxy-fuel 15 MWth burner test facility

Thomas Ochs[a,*], Danylo Oryshchyn[a], Rigel Woodside[a], Cathy Summers[a], Brian Patrick[b,*], Dietrich Gross[b], Mark Schoenfield[b], Thomas Weber[b], Dan O'Brien[b]

[a]*National Energy Technology Laboratory, 1450 Queen Avenue SW, Albany, OR 97321 USA*
[b]*Jupiter Oxygen Corporation, 4825 N. Scott St., Suite 200, Schiller Park, IL 60176 USA*

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Abstract

Jupiter Oxygen Corporation (JOC), in cooperation with the National Energy Technology Laboratory (NETL), constructed a 15 MWth oxy-fuel burner test facility with Integrated Pollutant Removal (IPRTM) to test high flame temperature oxy-fuel combustion and advanced carbon capture. Combustion protocols include baseline air firing with natural gas, oxygen and natural gas firing with and without flue gas recirculation, and oxygen and pulverized coal firing with flue gas recirculation. Testing focuses on characterizing burner performance, determining heat transfer characteristics, optimizing CO_2 capture, and maximizing heat recovery, with an emphasis on data traceability to address retrofit of existing boilers by directly transforming burner systems to oxy-fuel firing.

Keywords: high flame temperature oxy-fuel combustion; untempered oxy-fuel flame; heat transfer in oxy-combustion; CO_2 capture with energy recovery; Integrated Pollutant Removal (IPR)

1. Introduction

The Jupiter Oxygen Corporation has constructed an oxy-fuel 15 MWth burner test facility at their Hammond Indiana research facility to test oxy-fuel combustion for advanced carbon capture (Figure 1). The facility is a multi-fuel test center with a 60,000 lb/hr mild superheat B&W package boiler, 105 TPD cryogenic oxygen plant, coal pulverizer, flue gas recirculation system, Integrated Pollutant Removal (IPR™) system (for carbon capture and heat recovery), and a highly accurate data collection system implementing extensive error analysis.

Oxy-fuel combustion products are high in CO_2 and H_2O which are good absorbers and emitters of infrared radiation. With the high effective flame temperatures of high-oxygen-concentration oxy-fuel firing, heat transfer

* Corresponding author (NETL) Tel.: 1-541-990-5443; fax: 1-541-967-5958
E-mail address: Thomas.Ochs@netl.doe.gov.
* Corresponding author. (JOC) Tel.: 1-219-746-5586; fax: 1-847-928-0795
E-mail address: B_patrick@jupiteroxygen.com.

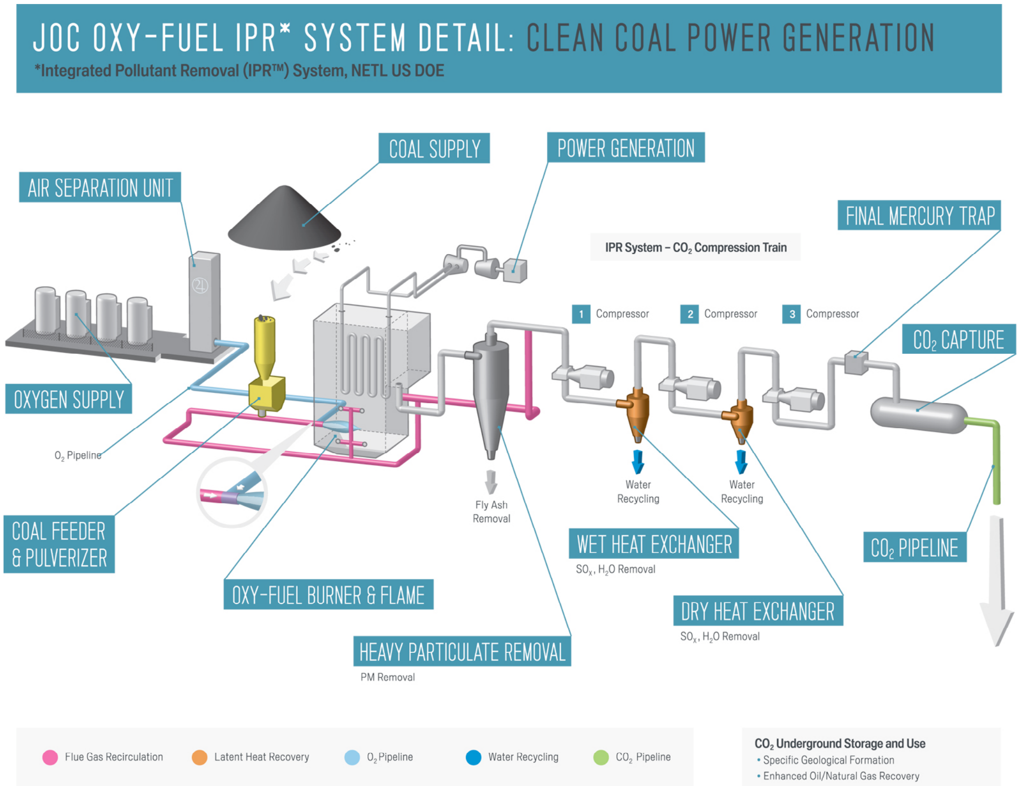

Figure 1. Pictorial representation of a clean coal power plant using Jupiter oxy-combustion combined with Integrated Pollutant Removal (IPR).

from the flame to boiler surfaces is increased due to the T^4 relationship of radiant transfer. Until this test facility was commissioned and operated there was only speculation and small scale tests on the effect of these high-temperature flames on boiler wall material. A scientific approach for heat transfer measurement was implemented in this system to better understand the radiant transfer through the active gas environment. Initial tests have started to better define heat transfer rates, heat transfer distribution in the boiler system, burner performance, coal combustion characteristics, flame properties, ash and slag behavior, and operational modes in this system. The quality of the data is important to ensuring that reliable engineering estimates can be made from the information we gather. The hope is to move the knowledge of oxy-fuel combustion forward based on these investigations and to supplement data coming from other organizations.

Most of the emphasis in oxy-fuel technology has been on using a pre-mix of oxygen and recycled flue gas at the burner, resulting in a lower flame temperature than pure oxy-fuel. Pure oxy-fuel generates a high temperature flame and low volume flue gas recycle at the burner with low excess oxygen. Jupiter's approach is to maintain the purity of the oxidant in order to have a flame with a high concentration of oxygen at the burner tip, thereby producing a very stable flame. This is combined with the NETL-developed IPR™ system to capture CO_2 and recover latent and sensible heat from the hot flue gas and from the compressors used to compress the gas to pipeline delivery pressure.

The 15 MWth test facility will provide quality data for better understanding oxy-fuel combustion using the high flame temperature Jupiter Oxygen heat transfer approach and the IPR™ system. Data collected on boiler efficiency, heat transfer, flame and burner characteristics, materials performance, and flue gas characteristics will be used by Jupiter Oxygen to refine their approach and by NETL to supplement their development of future computer modeling tools for oxy-combustion systems. This innovative approach in the field of carbon capture study will significantly add to the current knowledge base. The size of the test facility and burner capacities will accelerate technology development so that large scale demonstrations and, ultimately, commercialization can be realized for both new and retrofit power plants in the near future.

2. Concentrated Oxy-Combustion

The Jupiter Oxygen Corporation patented Oxy-Fuel system [1,2] is unique among all oxy-fuel systems currently on the market or being tested, in that it uses an untempered high temperature flame. All other known systems attempt to replicate an air-fuel flame temperature equivalency through the introduction of recycled gas into the oxygen stream to the burner. In addition, the introduction of the primarily carbon dioxide recycle gas into the oxygen stream can cause burner stability problems making the burner susceptible to flame out. The Jupiter Oxygen Corporation technology approach has the potential to be extremely stable, as proven in ten years of aluminum remelt furnace usage and previous boiler testing. Previous, smaller-scale boiler testing has also indicated efficiency gains over air-fired boilers (due to the capture of sensible and latent heat from the combustion products) and much more uniform heat transfer in the radiant zone due to the higher radiant effect of the untempered flame and the heat transfer characteristics of the gaseous combustion products. Current testing is designed to confirm and expand upon these results.

Table 1 describes the historical development of the JOC oxy-combustion technology, and illustrates a systematically executed plan to address scientific and engineering questions about oxy-combustion. After commercial development in aluminum melting furnaces, Jupiter made the initial technology transfer to boilers. Firing in a retrofit "D" type boiler Jupiter showed that the untempered high flame temperature oxy-fuel combustion flame can work. These tests were first done with natural gas and oxygen and then coal and oxygen. This work was followed up with computer modeling of a 400 MWe boiler and then by the construction and operation of an IPR unit to capture CO_2 with Jupiter oxy-fuel combustion. Currently Jupiter is operating the 15 MWth boiler where a detailed test program is collecting data on heat transfer with the untempered high temperature flame.

The operation of recycle systems in boilers is well-known and existing engineering principles will be used for this study. Integration of the thermal cycles of heating and cooling of the cryogenic plant will also be investigated in the overall engineering study.

3. Integrated Pollutant Removal (IPR^{TM})

The purpose of the IPR process is to minimize energy usage and costs (both capital and operational) of CO_2 capture and preparation for transportation. IPR is a staged approach to CO_2 capture that recovers heat from combustion products and uses that heat in the power plant. The integration of this low grade heat back into the cycle minimizes the energy penalty to operate these systems. The recovered heat can be applied to the steam cycle in much the same way as feedwater heaters or can be used as a source of process heat.

Capture and preparation include cooling, dewatering and compressing the combustion products to produce a dry, supercritical stream comprising CO_2 and tramp gases. Energy costs are reduced through recovery of sensible heat and latent heat of water condensation from flue-gas at each IPR cooling step. Capital cost reduction is realized through the smaller exhaust flow rate of oxy-firing. Operational costs are directly related to the purity of the recovered CO_2 product. There are, presently, no specifications for sequestration-bound CO_2, with the exception of CO_2 intended for enhanced oil recovery (EOR). EOR presently requires a high purity CO_2 stream resulting in a high cost for the product. However, with no specifications for transport and injection of CO_2 in deep saline aquifers or reactive geological formations, there may be additional cost reductions available by supplying a less pure CO_2 product. At a minimum for this application, fine particulates and water must be removed [3]. Research is underway to specify compositions suitable for the sequestration of oxy-combustion-derived CO_2 products in geological formations. Allowing tramp gases such as nitrogen, argon, and oxygen in the CO_2 product avoids additional separation steps reducing both capital and operational costs. In addition, laboratory research has demonstrated that spiking CO_2 with SO_2 may enhance carbonate mineral formation for some geological materials [4]. If formations can be shown to take SOx along with the other trace gases the cost of CO_2 separation using IPR can be greatly reduced. For these reasons the present tests are investigating CO_2 streams both with SOx removed and with SOx left in the system.

4. The Test Facility

The Jupiter Oxygen oxy-fuel burner test facility (Figure 2) is located in Hammond, Indiana. The 30,000 sq. ft. test facility (area does not include the cryogenic plant) consists of a 60,000 lb/hr super-heated steam boiler, 105 ton per day cryogenic plant, data collection system, and the necessary equipment to supply and control a variety of fuel sources, including pulverized coal and natural gas. The test facility was built to support a project of this magnitude, and will be available for the duration of the project.

Table 1. This chart summarizes the development process for Jupiter's Oxy-Fuel system to date. See references 1-9 for cited publications.

	Phase I	**Phase II**	**Phase III**	**Phase IV**	**Phase V**	**Phase VI Current**
Project Title	Proof of concept oxy-fuel process	Commercialization of oxy-fuel melters for aluminum	Viability testing of JOC oxy-fuel concept for boilers	Computer modeling for boiler retrofit including IPR	IPR demonstration using JOC coal-fired test chamber as CO_2 source	Enhanced test facility and IPR demonstration phase
Summary	Fired NG and oxygen in test melt furnace at up to 10 MMbtu's	Applied system based on commercially available components for production aluminum melting	JOC coal firing of Keeler D boiler on coal and NG with high purity oxygen	GE GateCycle computer modeling JOC and the NETL	JOC firing of test chamber to generate CO_2 for NETL IPR testing	Coal firing of 15MWth boiler on Illinois #6 coal with slip stream CO_2 capture using NETL IPR unit built of commercially available components
Dates of Performance	1995 to 1997	1997 to 2001	June 2002 to February 2003	January 2003 to January 2004	September 2004 to December 2004	April 2007 to current
Project Objectives	To determine what parameters are significant for operation in a melting furnace for aluminum using oxygen and fossil fuels. To test burners and controls.	To specify, test and operate commercial scale burners and controls. To confirm the accuracy and reproducibility of components and the operational economics for aluminum melting.	Proof of coal fired JOC oxy-fuel application to a boiler	To balance heat transfer in a boiler using 100% oxy-fuel firing at high temperature and recycle gas. To show by computer model that 95% and greater CO_2 capture is possible.	Pilot plant slip stream proof of viability of NETL IPR system	Coal firing of 15MWth boiler on Illinois #6 coal with slip stream CO_2 capture using NETL PIR unit built of commercially available components.
Location	Jupiter Aluminum Corporation test facility	Jupiter Aluminum Corporation production melters	JOC test facility	With NETL modeling	JOC test facility	JOC test facility
	Hammond, IN	Hammond, IN	Hammond, IN	Hammond, IN Albany, OR	Hammond, IN	Hammond, IN
Sponsorship	Jupiter Aluminum Corporation	Jupiter Aluminum Corporation	JOC	JOC	NETL and JOC	NETL and JOC
Thermal Capacity	10 MMbtu/hr	40 MMbut/hr	1.5 MWth	400 MWe	75 KW/hr	15 MWth
Fuel	NG and oil	NG and oil	NG and coal	Coal	NG and low sulfur coal	NG and high sulfur coal
Flue Gas Recycle	Not applicable for aluminum	Not applicable for aluminum	Test 0 to theoretical air volume	Test 0 to theoretical air volume	Test 0 to theoretical air volume	Test 0 to theoretical air volume
Burner Technology	Jupiter burners, Maxon burners	Jupiter burners, Maxon burners	Maxon test burner and Jupiter burners	Maxon test burner and Jupiter burners	Maxon test burner	Maxon 25 MWe commercial sized burner
Instrumentation	Non PLC based	Computer based data for production in plant	PLC based– minimal data	Complete integrated control	PLC based – minimal data	PLC and LabView – full instrumentation
Emission Controls	Baghouse	Baghouse	No	Full IPR system	Full IPR system	Baghouse and cyclone, IPR system
Key Results	Operation of a refractory lined melter without oxidation of metal and no material changes to furnace	Successful long term commercial operation with decrease in fuel usage of 70%	Retrofit concept feasible, decrease in fuel usage of 16% for natural gas	Feasible to balance heat transfer in a boiler using 100% oxy-fuel burners and recycle flue gas	Concept feasible capture of 80% of CO2 at pressures which showed that 95+% is feasible	Proof of commercial burner and IPR scale up
Publications	[1,2]	[5]	[6]	[7,8]	[9,10]	[11]

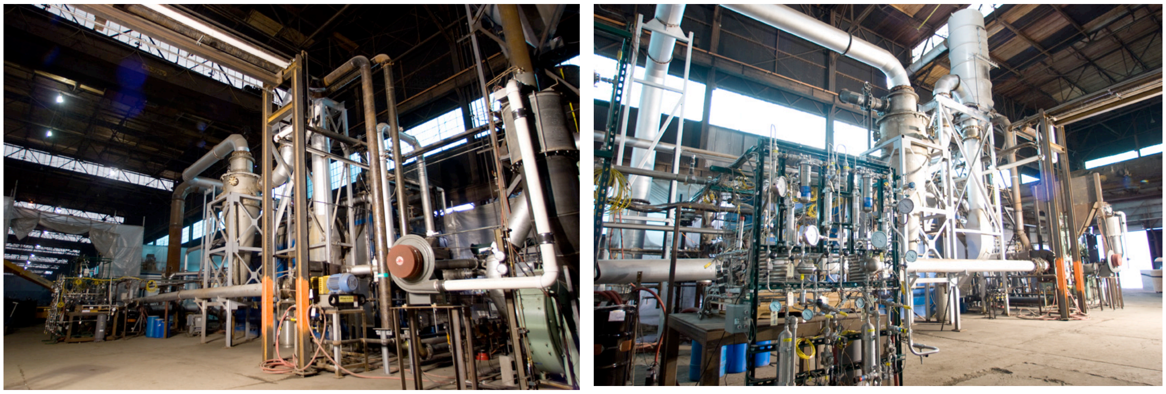

Figure 2. Photos of the burner test facility.

The functional design of IPR™, as installed at the Jupiter Oxygen Burner Test Facility, allows it to take in oxy-fired combustion products at stack temperature, then to scrub this incoming stream in a direct-contact heat exchanger, transferring latent and sensible heat into cooling water while scrubbing SOx from the gas (if needed). Indirect heat exchange (as in a condensing economizer) is another method applicable to this inlet step. Following this initial condensation and scrubbing, IPR compresses and dries the combustion products. Compression occurs in stages which are followed by intercooling. In the intercooling stages, IPR recovers energy from the heat of compression and latent heat of condensation into power-plant working fluids such as feedwater, as well as condensed water for treatment and use as clean process water. The final products are a dry, CO_2-rich supercritical fluid stream for geological sequestration, a stream of captured pollutants from the combustion products, and a stream of clean water. The installation at the Jupiter Oxygen's test facility is designed to capture more than 95% of the CO_2 fed to it and produce approximately 90% pure CO_2.

The current IPR installation at Jupiter Oxygen's test facility uses standard process equipment to treat a bleed stream of oxy-coal combustion products from the combustion product recirculation loop. Figure 3 shows IPR process flows. The gas enters (1) the IPR installation at about 400º F and flows into a glass-pipe spray tower (2). In the tower, the gas rises countercurrent through a spray stream which can contain a reagent such as sodium carbonate solution when SOx is being removed. Condensed combustion-product water (3) and spray water are cooled (4) and partially recirculated to the tower spray inlet (5). The balance of the water leaving the tower is removed from the process for treatment outside IPR (6). Temperature, chemical composition, and flow rate of the spray water are variable for experimentation. The tower is instrumented for temperature and pressure. Scrubbed gas leaves the tower through a coalescing filter (to remove spray carry-over) and enters a 2-stage, reciprocal compressor (7). This

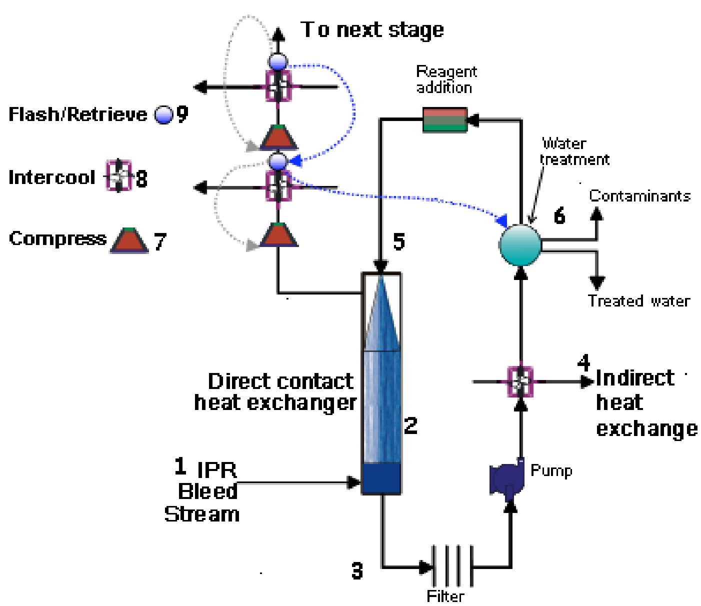

Figure 3. Cartoon of IPR process flows (Note the retention – dashed arrows – of dissolved CO_2 from intercooler condensates.)

compressor is "off-the-shelf" and has had its air-cooled intercooler replaced with a water-cooled, counter-flow heat exchanger (8). The gas and water sides of these heat exchangers are instrumented for temperature and pressure. Inlet temperature and flow-rate of water to each heat exchanger are variable for experimentation. Following each stage of compression, gas has been cooled and the condensed water allowed to separate into a water-collection vessel (9). Periodically, these collection vessels are opened, returning dissolved gas (shown by gray arrows) to the IPR gas-stream and removing accumulated water from IPR for treatment in a separate operation (see blue arrows).

5. Purposes and Methods

The underlying hypotheses being tested are that increased flame temperature will result in

- increased heat transfer in the radiant section,
- no increase in damage to boiler materials,
- an increase in the total heat transfer in the system,
- and a decrease in fuel usage when compared to other carbon capture approaches.

Heat transfer uniformity, corrosion, and erosion will be evaluated to answer concerns regarding the effect of higher temperature flames and oxy-fuel combustion products. This phase of testing also will establish the overall relative burner performance and monitor the properties of the flame.

The equipment used to collect data includes thermocouples inside the boiler, spectral analysis equipment at boiler viewports, chordal thermocouples in boiler tubes, and Gardon heat flux meters in the boiler walls. Figure 4 shows some of the observation ports, temperature and heat flux devices that have been added to this boiler for measurements of heat transfer. Inputs of fuel, oxygen, and recycled combustion products are measured for composition, temperature, pressure and flow. Quantity and composition of outputs from the boiler are measured, including steam, ash, slag, and flue gases. Metal coupons will be mounted inside the boiler to measure internal

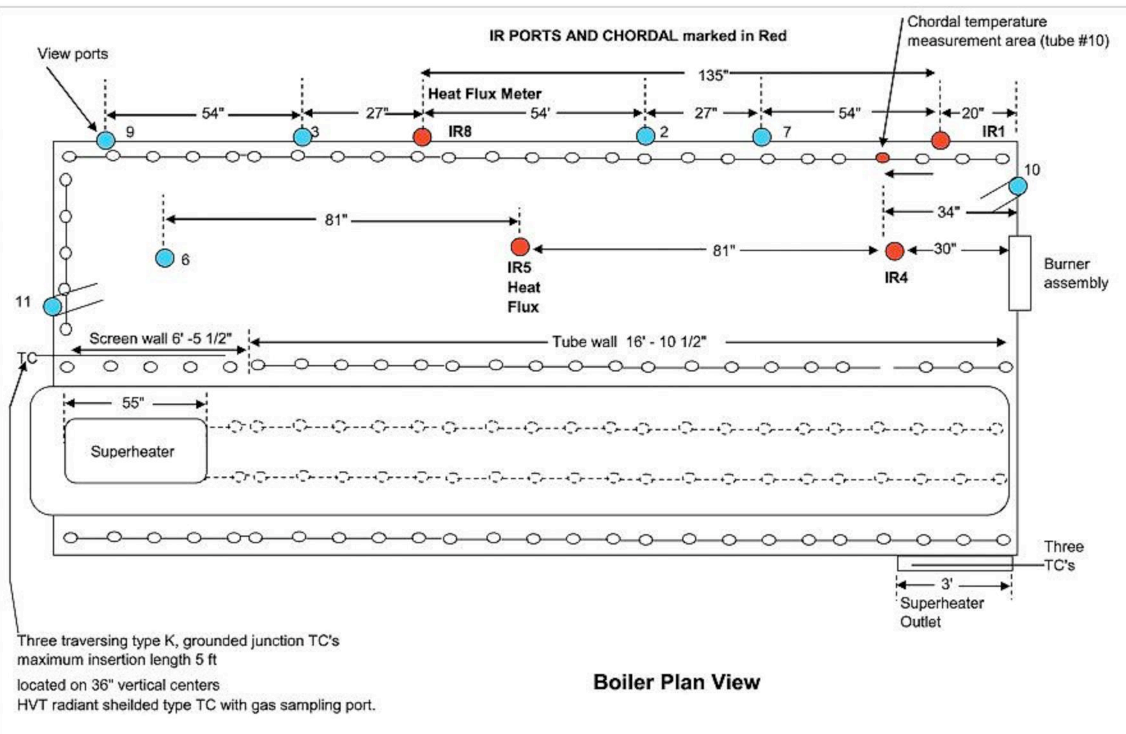

Figure 4. Plan view of boiler instrumentation for data collection

corrosion. The data collected will be analyzed with respect to the hypotheses as well as to data obtained from oxy-natural gas firing.

The IPR system is instrumented and provided with gas and liquid sample-collection ports. The instrumentation provides data on pressure, temperature, volumetric flow-rate, pH and oxygen concentration. Pressure, temperature and flow are measured continuously throughout the system. The pH in the recirculating spray-tower is continuously monitored. An on-board sensor tracks the oxygen content of gas leaving the second compression-stage intercooler. Samples of gas and liquid are taken periodically from points throughout the system. These samples are analyzed for composition at an outside laboratory. Liquid from compressor intercoolers is collected at process pressure to retain dissolved gases for analysis.

Data from IPR™ instrumentation will be used to calculate enthalpy change in flue-gas and of heat-exchanger cooling-water at each pressure stage. This will allow quantification of heat recovery. The rates of water condensation at each cooling step, which are affected by the operating parameters used in IPR, will also be quantified. Gas and liquid chemical analysis will show how gaseous components report to each process step of IPR. The quantification of oxygen and nitrogen, specifically, will indicate occurrences of air-infiltration into the boiler/IPR system. Acid-gas and water concentration are important metrics for condensate treatment and for characterization of the final IPR product and its readiness for pipeline transportation.

6. Results and Future Work

Current activities at the test facility include analysis of data generated during natural gas testing and shakedown for coal and oxygen operations. The 15 MWth boiler has been firing coal and oxygen since August of 2008. Operations will focus on execution of a test matrix designed to gather the information required to support the testing hypotheses.

Preliminary heat transfer results, which show the type of data that are acquired from the system, were obtained during shake-down oxy-natural-gas firing. Figure 5 shows temperatures as measured by thermocouples embedded in

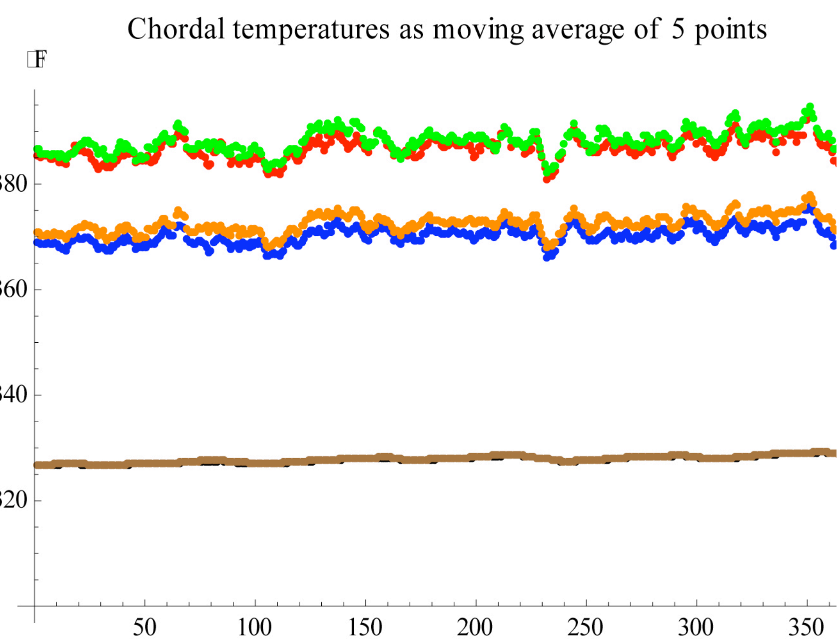

Figure 5: Measurement of heat transfer through the walls of a boiler tube using the technique of chordal temperature measurement. Sample number is along the x-axis, and temperature in °F on the y-axis.

the wall of a boiler tube (chordal thermocouples). Two of the thermocouples are located near the skin of the tube on the fireside and are shown by the red and green lines. Two more thermocouples are located at a measured distance into the wall of the tube in line with the first two thermocouples (data shown in orange and blue), also on the fireside. The difference in temperature between the two thermocouples (one at the skin and one deeper in the tube wall) directly indicates heat transfer rate. There is a fifth thermocouple (brown line) located on the back side of the tube (opposite the fireside) which measures the wall temperature on the non-illuminated side of the tube.

Shake-down operations of the IPR system have processed ambient, humid air. Data that can be expected from future tests include pressure and temperature histories of flue gas and cooling water, and calculated gas enthalpies. The test protocol for the IPR system will identify modes of operation that maximize heat recovery and minimize water use, produce gas composition data to enhance combustion characterization, and gather parameters useful for scaling up the IPR process.

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