APPENDIX B: CARBON DIOXIDE CAPTURE TECHNOLOGY SHEETS

OXY-COMBUSTION

OXY-COMBUSTION BOILER DEVELOPMENT FOR TANGENTIAL FIRING

Primary Project Goals

Alstom is developing and testing oxy-combustion technology for tangentially-fired (T-fired) boilers in retrofit and new power plant applications.

Technical Goals

- Design and develop an innovative oxy-combustion firing system for existing T-fired boilers that minimizes overall capital investment and operating costs.
- Evaluate the performance of oxy-combustion T-fired boilers in pilot-scale tests at Alstom's 15-MW_{th} Boiler Simulation Facility (BSF).
- Determine the boiler design and performance impacts for oxy-combustion.
- Evaluate and improve engineering and computational fluid dynamic (CFD) modeling tools for oxy-combustion.
- Develop the design, performance, and costs for a demonstration-scale oxy-combustion boiler and auxiliary systems.
- Develop the design and costs for both industrial and utility commercial-scale reference oxy-combustion boilers and auxiliary systems, which are optimized for overall plant performance and cost.

Technical Content

Initial screening studies were conducted to assess the impacts of a broad range of process variables and boiler design parameters on oxy-combustion boiler design, performance, and cost. This information was used to refine the test plan and establish design requirements for the 15-MW_{th} testing.

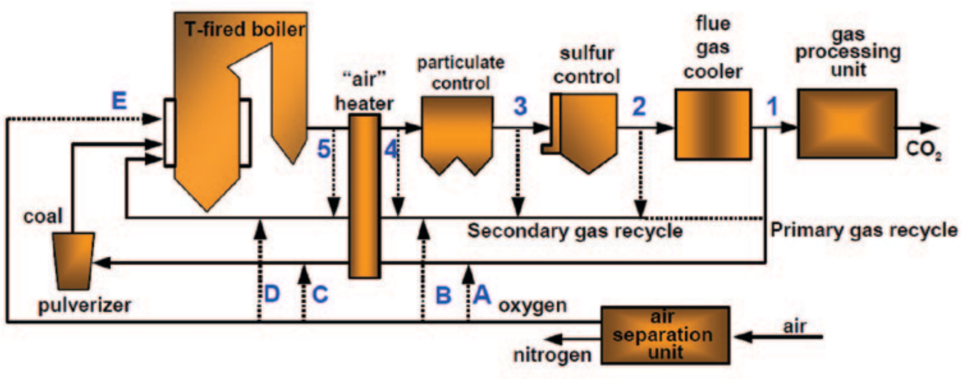

Figure 1: Simplified Oxy-Combustion Process Diagram

Technology Maturity:

Pilot-scale using actual flue gas, 120 tonnes CO_2/day

Project Focus:

Tangentially-Fired Oxy-Combustion Retrofits

Participant:

Alstom Power

Project Number:

NT0005290

NETL Project Manager:

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Principal Investigator:

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Partners:

Illinois Clean Coal Institute
North Dakota Industrial Commission
Utility Advisory Group (10 utility companies)

Performance Period:

9/30/08 – 9/30/13

Figure 1 is a schematic representation of an oxy-combustion process showing the location of a T-fired boiler and several possible take-off locations for flue gas recirculation (1–5) and locations for oxygen injection (A–E). The different take-off locations will affect variables in the recirculation stream (i.e., water, particulate, and sulfur content) and impact the size of equipment.

The screening studies included evaluation of the following variables: gas recycle take-off location, gas recycle composition, gas recycle ratio, oxygen injection concentration and distribution, windbox design, and separate over-fire air design. Both process modeling and CFD analysis were applied.

CFD simulations of the BSF and an 850-MWe supercritical T-fired boiler were developed and used to evaluate various oxy-combustion design options. The BSF models are being updated using boundary conditions and data from the BSF test runs to be compared with test measurements and validate predictions.

Alstom Power is conducting the pilot tests in its 15-MW_{th} BSF facility, shown in Figure 2. The BSF replicates the T-firing conditions in utility boilers. The BSF was modified for oxy-combustion operation and to provide flexibility to test over a broad range of conditions. The primary combustion test parameters evaluated include:

- Gas recycle rate and recycle sulfur capture rate.
- Distribution of gas recycle into the furnace.
- Excess oxygen.
- Oxygen injection location, distribution, and concentration.

Figure 2: Alstom 15 MW_{th} Boiler Simulation Facility

Key aspects of boiler operation that are being investigated under this project during the 15-MW_{th} pilot testing and during design studies are shown in Figure 3.

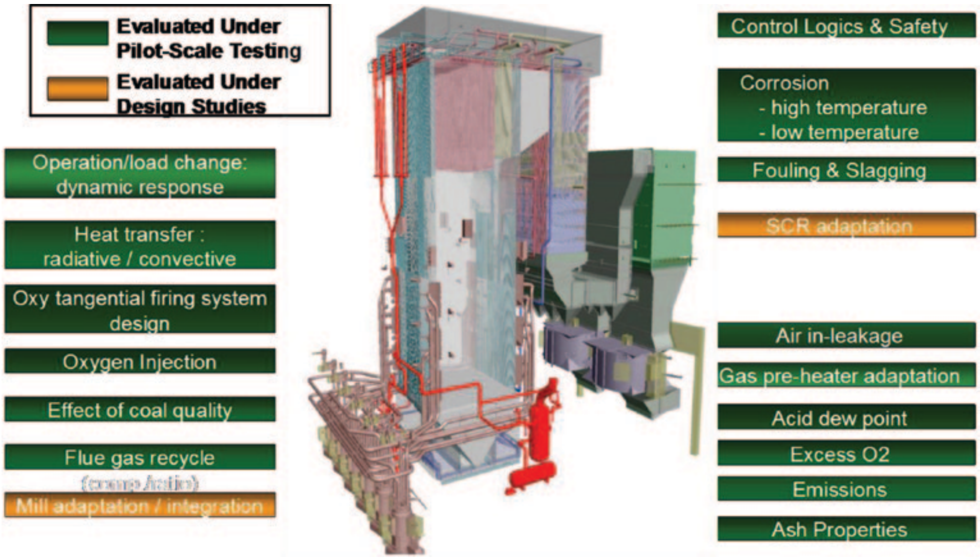

Figure 3: Aspects of Boiler Operation Requiring Assessment

The testing focuses on control of furnace heat release rates and heat transfer for boiler thermal performance during oxy-combustion, while obtaining good fuel burnout and control of emissions. Measurements are conducted to assess ash deposition and fireside corrosion, as well as sulfur trioxide (SO_3) formation and behavior of trace metals such as mercury.

Detailed furnace mapping measurements are also being performed to better understand behavior during oxy-combustion, as well as to provide comprehensive data sets for model refinement and validation. Furnace and convection pass temperatures are measured using suction pyrometers. Heated gas extraction probes are used with a dedicated gas analyzer system to measure in-furnace gas compositions. Incident heat fluxes to the furnace walls are measured using total heat flux probes and radiant heat fluxes are measured by ellipsoidal radiometer probes. Typical measurement planes are shown in Figure 4.

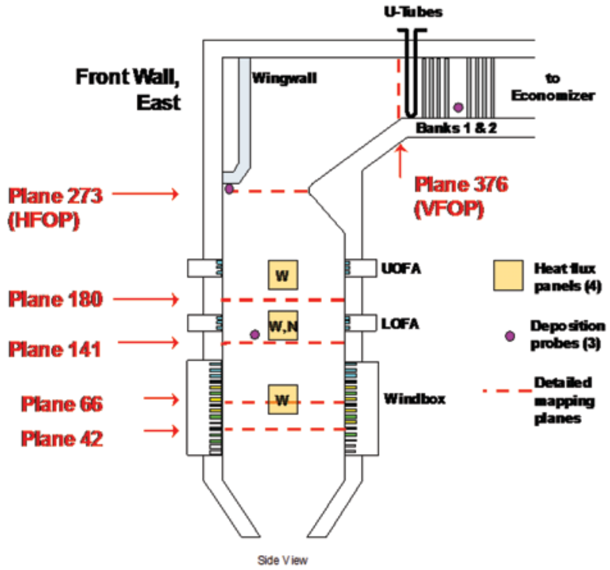

Figure 4: BSF Furnace Probe Measurement Planes

Results from the 15-MW_{th} testing, along with the refined modeling tools (CFD and dynamic simulations), are being applied to develop a basic design for a full-scale oxy boiler, which can be rapidly applied for demonstration. This will include the oxy-boiler design with advanced oxy-firing system and operational controls, as well performance and cost data. Additionally, large, commercial-scale oxy-boiler reference designs will be developed for industrial and utility applications, which are integrated and optimized for overall oxy-plant performance and costs, and to provide a vision for the final commercial product.

Technology Advantages

Oxy-combustion is a cost-competitive, near-term solution for carbon dioxide (CO_2) capture that offers a relatively low technical risk due to use of conventional components. It can be used in new and retrofit applications, and has the potential for greater than 90% CO_2 capture.

R&D Challenges

- Understanding difference from air-firing in pollutant formation, ash deposition, fireside corrosion, and heat transfer rates in an oxy-combustion boiler, as well as the control of air in-leakage.
- Application of this knowledge to reduce design risks and optimize designs for performance and costs.
- Overall integration to provide commercially attractive CO_2 reduction solutions.

Results To Date/Accomplishments

- Completed CFD screening evaluations.
- Completed modifications to the BSF for oxy-combustion operation to permit the firing under both air and oxygen, as well as with several flue gas recycle configurations and oxygen injection methods.
- Completed pilot-scale testing over a range of coal types, including sub-bituminous, low-sulfur bituminous, high-sulfur bituminous, and North Dakota lignite. Testing included both oxy- and air-firing tests, which examined the impacts of combustion

and oxy-process parameters on boiler design and operation for each of the coals. Test parameters included re-circulated flue gas ratio, effect of oxygen concentration and oxygen distribution into the furnace, re-circulated flue gas take-off location, total excess oxygen, furnace combustion staging, air in-leakage rates, and reduced load operation. A brief overview of results in some key areas examined is below.

- General oxy-fired operation – Stable operation over a broad range of test conditions. Able to produce flue gas with greater than 90% CO_2 concentration (dry basis).
- Combustion – Good performance during both air- and oxy-combustion testing for all coal types. Able to operate at low excess oxygen [less than 2% oxygen (O_2) at the economizer outlet]; low (near zero) carbon monoxide (CO) emissions; and low carbon in fly ash.
- Nitrogen oxide (NO_x) emissions – Lower NO_x emissions with oxy-combustion than air-firing. NO_x emissions were generally more than 50% lower for oxy-fired than air-firing under similar staged combustion conditions.
- Heat transfer – Able to control furnace heat flux and temperature profiles during oxy-firing to be similar to those for air-firing.
- SO_3 formation – Sulfur dioxide (SO_2) to SO_3 conversion appears to be similar to air-firing; however, SO_3 concentrations could be much higher for oxy-combustion depending on recycle scheme.
- Ash deposition – Appeared generally similar to air-firing in terms of deposits physical characteristics and in composition.
- Waterwall corrosion – Appeared generally similar to air-firing.

Next Steps

- Complete remaining two 15-MW_{th} test campaigns: (1) with Schwarze Pumpe test fuel to provide a link with the Vattenfall 30-MW_{th} oxy-combustion pilot plant, and (2) for evaluation of second generation oxy-combustion concepts.
- Perform bench-scale corrosion evaluation in order to provide supplemental data to support the pilot results and help define material requirements.
- Complete engineering tools and CFD modeling refinement and validation.
- Develop oxy-combustion boiler design package with performance and costs for full-scale demonstration application.
- Develop oxy-combustion boiler references designs for utility and industrial applications for future large-scale commercial products.

Final test results are scheduled to be issued in January 2012. The overall project is scheduled to be completed by September 2013.

Available Reports/Technical Papers/Presentations

General project information is available on DOE/NETL website at: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/oxy-combustion/tangential.html

"Oxy-Combustion: A Sound CCS Solution Built From Pilot Operation." Power Gen International – 2010, December 14, 2010, Orlando, FL.

"SO_3 Emissions From a Tangentially-Fired Pilot Scale Boiler Operating SO_3 Emissions From a Tangentially-Fired Pilot Scale Boiler Operating Under Oxy-Combustion Conditions." 2010 AIChE Annual Meeting, November 10, 2010, Salt Lake City, UT.

"Oxy-Combustion Boiler Development for Tangential Firing," Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, Pittsburgh, PA, September 2010. http://www.netl.doe.gov/publications/proceedings/10/co2capture/index.html

"Alstom's Oxy-Combustion Technology Development – Update on Pilot Plants Operation." 35th International Technical Conference on Clean Coal and Fuel Systems, June 6–10, 2010, Clearwater, FL.

"Assessment of Oxy-Combustion Impacts on Boiler Design and Performance During 15 MW_{th} Pilot-scale Testing." 9th Annual Carbon Capture and Sequestration Conference, May 10 13, 2010, Pittsburgh, PA.

"Update on Alstom's Oxy-Combustion Technology Development." 12th Annual ELECTRIC POWER Conference and Exhibition, May 18 20, 2010, Baltimore, MD.

"Alstom's Oxy-Firing Technology Development and Demonstration – Near Term CO_2 Solutions." 34th International Technical Conference on Coal Utilization and Fuel Systems. June 2009.

"Oxy-Combustion Boiler Development for Tangential Firing." Presented at the annual NETL CO_2 capture technology for existing plants R&D meeting. March 2009.

"Oxy-Combustion PC and CFB Solutions – A Promising Option for CO_2 Capture." Presented at 8th Annual Conference Carbon Capture and Sequestration, Pittsburgh, PA, May 2009.

"Oxy-Firing Technology – Pilot Testing Leading to Large-Scale Demonstration." 11th Annual Electric Power Conference, Chicago, IL, May 2009.

OXY-COMBUSTION BOILER MATERIAL DEVELOPMENT

Primary Project Goals

Foster Wheeler is conducting a laboratory test program to assess the corrosion characteristics of oxy-combustion relative to air-fired combustion for pulverized coal (PC)-fired boilers; identify the corrosion mechanisms involved; and determine oxy-combustion's effects on conventional boiler tube materials, conventional protective coatings, and alternative materials and coatings when operating with high to low sulfur coals.

Technical Goals

- Conduct computational fluid dynamic (CFD) modeling of air- and oxy-fired PC boilers operating with high, medium, and low sulfur coals to determine the flue gas compositions that will exist throughout these units and especially along the furnace waterwalls where highly corrosive micro-climates can exist.
- Conduct corrosion tests using coupons of conventional and advanced boiler tube materials that are coated with deposits representative of low to high sulfur coals and exposed to the CFD-predicted oxy-combustion and air-fired flue gases for up to 1,000 hours in electric furnaces using synthesized gases from pressurized cylinders.
- Conduct post-test macroscopic and microscopic analyses of the material coupons to identify corrosion mechanisms, evaluate the corrosiveness of oxy-fired flue gas relative to air-fired flue gas, and identify materials suitable for oxy-combustion.

Technical Content

An oxy-combustion boiler retrofit will utilize flue gas recycle to maintain the heat absorption of the original air-fired boiler and limit the combustion temperature. With air nitrogen (N_2) eliminated, and with the recycle consisting of carbon dioxide (CO_2) and water vapor (H_2O), along with corrosive products of combustion, the level of reducing and corrosive gases in the boiler [e.g., carbon monoxide (CO), sulfur dioxide (SO_2), sulfur trioxide (SO_3), hydrogen sulfide (H_2S), and hydrogen chloride (HCl)] will increase and could cause increased corrosion. To assess the corrosiveness of oxy-combustion flue gas, coupons of conventional and advanced waterwall and superheater/reheater materials will be exposed to oxy- and air-fired flue gases in electric tube furnaces. Rectangular shaped coupons, typically 19 mm (¾ inch) wide by 25 mm (1 inch) high by 3 mm (⅛ inch) thick, will be used to investigate tube materials, tube welds, and tube weld overlays; bullet shaped coupons, typically 19 mm (¾ inch) in diameter by 38 mm (1½ inch) high, will investigate thermal spray coatings. The conventional and advanced materials to be tested are listed in Table 1 and Table 2.

Technology Maturity:

Laboratory evaluation using synthetic gases

Project Focus:

Evaluation of Boiler Materials for Oxy-Combustion

Participant:

Foster Wheeler Corporation

Project Number:

NT0005262

NETL Project Manager:

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Partners:

None

Performance Period:

10/1/08 – 9/30/11

Table 1: Waterwall Materials

	Material	Description	Boiler Use	Nominal Composition
1	Tube	SA210-A1	Conventional	0.27% Carbon
2	Tube	SA213-T2	Conventional	1/2 Cr-1/2 Mo
3	Tube	SA213-T11	Conventional	1-1/4 Cr-1/2 Mo
4	Weld	T11 to T11	Conventional	1-1/4 Cr-1/2 Mo
5	Weld Overlay	309L StnStl	Conventional	24 Cr
6	Weld Overlay	Inconel 622	Conventional	21 Cr-55 Ni
7	Weld Overlay	VDM Alloy 33	Conventional	33 Cr-31 Ni
8	Thermal Spray	IGS UTEx 5-450	Relatively New	40 Cr-55 Ni
9	Thermal Spray	IGS UTEx 5-480	Relatively New	25 Cr-60 Ni
10	Thermal Spray	IGS UTEx 5-500	Relatively New	15 Cr-80 Fe

Table 2: Superheater/Reheater Materials

	Material	Description	Boiler Use	Nominal Composition
1	Tube	T22	Conventional	2-1/4 Cr-1 Mo
2	Tube	304H StnStl	Conventional	18 Cr-8 Ni
3	Tube	347H StnStl	Conventional	18 Cr-9 Ni
4	Tube	T91/T92	New Boilers	9 Cr
5	Tube	NF709	New Boilers	20 Cr-25 Ni
6	Tube	HR3C	New Boilers	25 Cr-20 Ni
7	Weld Overlay	Inconel 622	Conventional	21 Cr-55 Ni
8	Weld Overlay	VDM Alloy 33	Conventional	33 Cr-31 Ni
9	Weld Overlay	Inconel 72	Conventional	44 Cr-55 Ni
10	Welded Coupon	T22–304H	Conventional	1-1/4 Cr-18 Cr

The coupons, mounted in racks and inserted in electric tube test furnaces (see Figure 1), will be exposed for 1,000 hours to synthesized air- and oxy-fired flue gases. Foster Wheeler will conduct CFD analyses of nominal 500-megawatt electric (MWe) air- and oxy-fired boilers (see Figure 2) to determine the range of flue gas compositions that will exist throughout these boilers and especially along their furnace walls where highly corrosive micro-climates can exist; based on those ranges, gas compositions will be selected for the corrosion tests. The test gases will be synthesized/blended from gas cylinders and consist of varying concentrations of CO_2, H_2O, N_2, CO, SO_2, H_2S, and HCl.

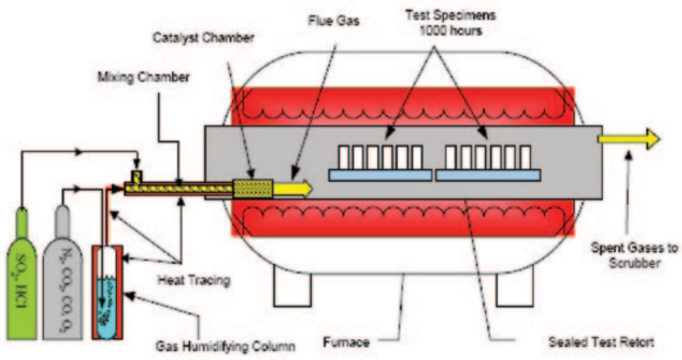

Figure 1: Coupons Mounted in Racks and Inserted in Electric Tube Test Furnaces

The material coupons will be coated with three types of synthetic ash deposits representative of high, medium, and low sulfur coals. The deposits will be produced from reagent grade powders that are mixed and applied to the coupons as a paste. The waterwall materials will be tested at three temperatures: 399 °C, 468 °C, and 538 °C (750 °F, 875 °F, and 1,000 °F); the superheater/reheater materials will be tested at: 538 °C, 593 °C, and 649 °C (1,000 °F; 1,100 °F; and 1,200 °F)—temperatures that span the range of boilers operating at subcritical and supercritical pressure. Upon completion of exposure testing, the condition of the coupons will be evaluated macroscopically and microscopically and the materials will be assessed for their suitability for oxy-combustion.

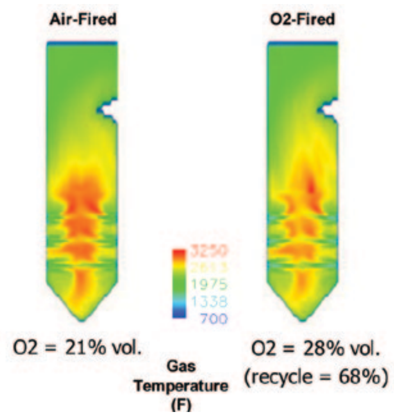

Figure 2: Example of Foster Wheeler CFD Analyses

Technology Advantages

This project will identify the corrosion mechanisms that occur under oxy-combustion and assess the suitability of conventional and advanced boiler materials for this new combustion environment.

R&D Challenges

Flue gas recycle used for the oxy-combustion process could increase corrosion of boiler materials.

Results To Date/Accomplishments

- CFD analyses of nominal 500-MWe PC boilers (wall- and tangential-fired) have identified the bulk flue gas compositions and waterwall micro climates that will exist in these units under air- and oxy-firing.
- The most corrosive gas compositions together with intermediate levels of corrosiveness for each combustion mode were selected for use in laboratory electric furnace corrosion studies.
- The boiler materials coupon testing is in progress and includes five 1,000-hour test series; four test series investigate furnace waterwall micro climates that range from highly reducing (20% CO) to mildly oxidizing (1% O_2) conditions, and one test series investigates the oxidizing (nominally 3% O_2) superheater/reheater condition. The superheater/reheater and three furnace wall test series have been completed and the fifth and final test series (waterwall with 5% CO) began in January 2011. An example of some preliminary corrosion test results are shown below in Figure 3 for waterwall materials exposed to 2% CO air- and oxy-fired micro-climates at 875 °F for 1,000 hours with three levels of iron sulfide (FeS) deposits.

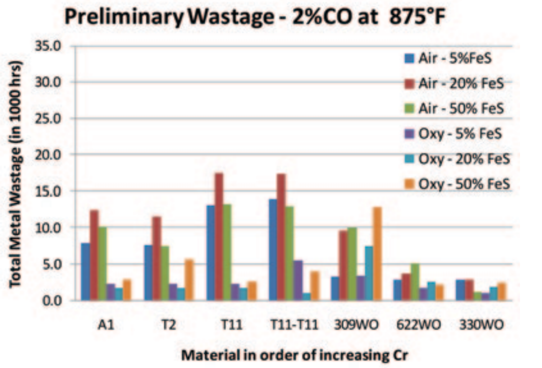

Figure 3: Example of Preliminary Corrosion Results for Waterwall Materials

- The preliminary 1,000-hour results show that under oxy-combustion:
  - The effect of oxy-combustion on test coupon corrosion varies with the type of material, deposit, and temperature.
  - Superheater/reheater and waterwall wastages are generally less than under air-firing.
  - Superheater/reheater and waterwall wastage increases with increasing temperature and tends to decrease with increasing chromium concentrations.
  - Waterwall wastages at 2% CO were higher than at 1% O_2.

Next Steps

- Complete the planned coupon test matrix.
- Complete macroscopic and microscopic examination of the material coupons to identify corrosion mechanisms and material suitability for oxy-combustion.

Final test results will not be available until after the September 2011 project completion date.

Available Reports/Technical Papers/Presentations

General project information is available on DOE/NETL website at: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/oxy-combustion/material.html

"Oxy-Combustion Boiler Material Development," Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, Pittsburgh, PA, September 2010. http://www.netl.doe.gov/publications/proceedings/10/co2capture/index.html

"Oxy-Combustion Boiler Material Development," Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, March 2009, Pittsburgh, PA.

CHARACTERIZATION OF OXY-COMBUSTION IMPACTS IN EXISTING COAL-FIRED BOILERS

Primary Project Goals

Reaction Engineering International (REI) is developing analytical tools to characterize and predict impacts of carbon dioxide (CO_2) flue gas recycle (FGR) and burner feed design on flame characteristics, fouling, slagging, and corrosion, inherent in the retrofit of existing coal-fired boilers for oxy-combustion. Investigations include laboratory-, bench-, and pilot-scale tests, as well as computer simulations of pilot-scale and full-scale systems.

Technical Goals

- Utilize multi-scale testing and theory to develop:
  - Fundamental data that describe flame characteristics, corrosion rates, and ash properties during oxy-combustion coal firing.
  - Validated mechanisms that describe oxy-combustion processes.
  - Firing system principles that guide oxy-burner design and FGR properties.
- Incorporate validated mechanisms into a computational fluid dynamics (CFD) model to evaluate full-scale oxy-combustion retrofit designs:
  - Predict flame characteristics and surface impacts for different full-scale oxy-firing designs and FGR properties.

Technical Content

REI is characterizing and predicting the performance and operational impacts of oxy-combustion retrofit designs on existing coal-fired boilers. The project focus is to develop tools to characterize and predict impacts of FGR and burner feed design on flame characteristics [burnout, nitrogen oxide (NO_x), sulfur oxide (SO_x) and fine particle emissions, heat transfer], fouling, slagging, and corrosion. Testing includes production of multi-scale experimental data focused on burner design, char oxidation, soot evolution, ash characterization and deposition, and corrosion. Mechanisms capable of describing these phenomena under air- and oxy-combustion conditions are being developed and validated using the data generated during experimentation and from the literature. The mechanisms are being implemented into a CFD code and an existing coal-fired utility boiler is modeled under air- and oxy-combustion conditions to identify the likely impacts of retrofit.

This project is tailored to both identify potential impacts of the oxy-combustion retrofit of existing coal-fired utility boilers (through multi-scale experiments) and to develop tools that allow accurate prediction of these impacts (through mechanism development). Experiments are performed on three different scales: (1) a bench-scale optical entrained flow reactor is used to elucidate the impact of oxy-combustion flue gas composition on the rate of char oxidation; (2) a 100-kW lab-scale combustor is used to characterize the effects of FGR on ash characteristics; and (3) a 1.2-MW pilot-scale combustor is used to investigate burner and firing system principles, deposition, corrosion, and radiative heat transfer, including soot evolution. The data from these experiments is used to guide development of mechanisms that may be used to describe char oxidation, deposition (slagging and fouling), corrosion, and soot evolution. The data generated is used to produce an overview of firing system principles for oxy-combustion that should help guide design of full-scale firing systems.

Technology Maturity:

Laboratory-, bench-, and pilot-scale; simulated and actual flue gas; 0.3-8 tonnes of CO_2 per day

Project Focus:

Characterization of Oxy-Combustion Impacts

Participant:

Reaction Engineering International

Project Number:

NT0005288

NETL Project Manager:

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Partners:

Brigham Young University
Corrosion Management LTD
PacifiCorp
Praxair, Inc.
Sandia National Laboratory
Siemens Energy, Inc.
Southern Company
University of Utah
Vattenfall AB

Performance Period:

10/1/08 – 9/30/11

Bench-Scale Optical Entrained Flow Reactor Experiments

Bench-scale experimentation is conducted at Sandia National Laboratories to further elucidate the behavior of char in an oxygen (O_2)-enriched FGR gas matrix. These experiments are conducted in Sandia's optical entrained flow reactor and associated particle-sizing pyrometry diagnostics.

100 kW Oxy-Fuel Combustor (OFC) Experiments

Data related to ash characterization and deposition is collected using experiments conducted in the University of Utah's 100-kW Oxy-Fuel Combustor (OFC), shown in Figure 1. The furnace consists of an OFC chamber and radiant zone in the vertical section, followed by a horizontal convective section where temperature profile is prescribed through adjustment of independently controlled cooling coils to simulate practical furnace temperature profiles.

These air- and oxy-fired experiments focus primarily on effects of FGR on ash chemistry, under practical time/temperature/particle composition conditions. Multiple modes of gas recycle are tested to investigate FGR conditions ranging from hot, moist, and particle-laden gases to clean CO_2. This information provides insight into how slagging and fouling could be impacted under oxy-firing conditions. Measurements include sampling of ash aerosol using low-pressure impactors and isokinetic dilution probes. In addition, mobility particle sizers determine ultrafine (sub-micron) particle concentrations and particle size distributions, and energy-dispersive X-ray spectroscopy (EDS) and computer-controlled scanning electron microscopy (CCSEM) techniques are used to identify ash compositions.

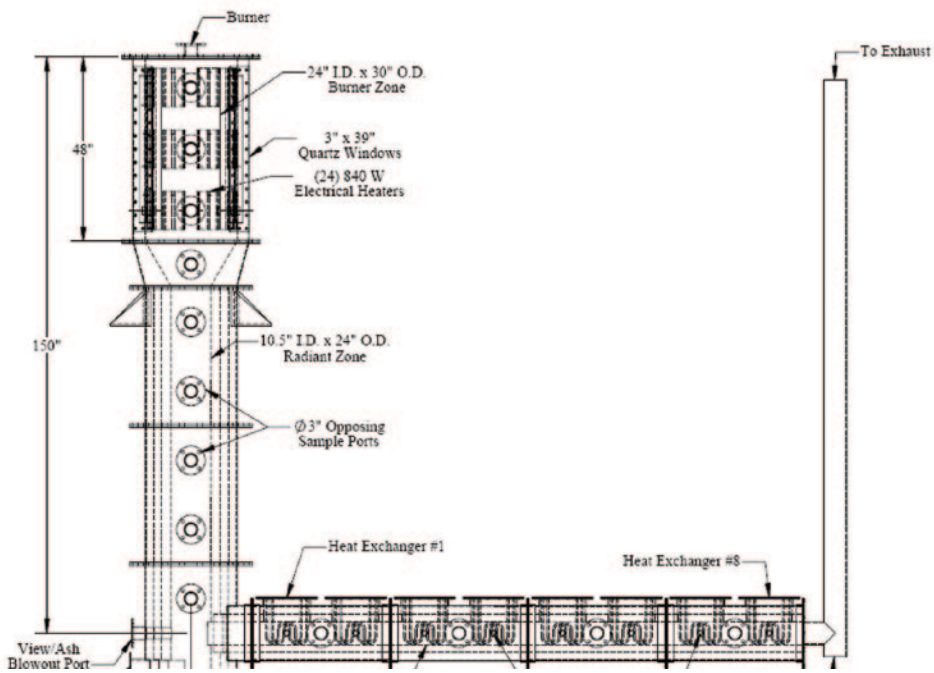

Figure 1: Diagram of 100-kW Oxy-Fuel Combustor (OFC)

Figure 2: Pilot-Scale Combustion Facility (L1500)

1.2 MW Pilot-Scale Furnace (L1500) Experiments

Pilot-scale experiments are performed in a 1.2-MW pulverized coal furnace (L1500). These experiments are designed to investigate firing system configuration impact on flame stability and heat transfer, soot evolution and water wall, and superheat material corrosion. A picture of the L1500 is shown in Figure 2. Four weeks of parametric testing were performed in the L1500 to develop practical guidelines that allow optimized operation of an actual burner under oxy-combustion conditions with FGR. Burner operating parameters of interest include:

- Variable O_2, FGR, and coal distribution in the burner.
- Variable FGR ratios that produce 27% and 32% O_2 in the O_2/FGR mixture.
- Variable burner stoichiometric ratio within the range of 0.8–1.2.
- Targeted O_2 injection.
- Furnace staging of FGR independent of burner conditions.

Six weeks of testing were performed in the L1500 to characterize corrosion under both air- and oxy-combustion conditions. Results from previous experiments were used to identify regions in the furnace for installation of the corrosion probes where deposition, heat flux, and flue gas compositions are favorable for corrosion and relevant for full-scale utility boilers. The parameters of interest in the corrosion test include:

- Air- and oxy-fired conditions.
- Powder River Basin (PRB) and bituminous coals.
- Optimized O_2, FGR, and coal distribution in the burner, from previous experiments.
- Variable flue gas recirculation ratio, within the limits from previous experiments.
- Variable burner stoichiometric ratio, within the limits from previous experiments.

Measurements performed in the pilot-scale furnace include:

- Flue gas composition [O_2, CO_2, carbon monoxide (CO), NO_x, mercury (Hg), and sulfur dioxide (SO_2)] using existing measurement equipment.
- Unburned carbon in ash, using loss on ignition analysis.
- Flame attachment, using ultraviolet sensors and cameras.
- Real-time corrosion measurements.
- Deposition rate and composition at the corrosion locations.
- Heat flux at the corrosion locations and other locations in the furnace.
- Local flue gas temperatures, using suction pyrometry.
- Soot volume fraction using the two-color extinction method.

Technology Advantages

- Enable the development of validated combustion mechanisms specifically designed for oxy-combustion with FGR for retrofitting existing coal-fired boilers.
- Identify firing system principles that guide oxy-burner design and potential retrofit strategies.
- Quantify impacts of FGR properties on ash deposition.

- Quantify impacts of oxy-combustion firing on corrosion of typical boiler waterwall and superheat materials.
- Develop the capability to assess the performance and optimize the retrofit of oxy-combustion to a full-scale existing boiler to

R&D Challenges

- Ability to control and quantify how much air-in leakage occurs inside the OFC and L1500 furnace during the experiments.
- Development and operation of a coal-fired research burner specifically designed to span a range of coal/O_2/FGR injection strategies and operating conditions.
- Correlation of experimental data with mechanisms and model predictions in order to provide adequate mechanism/model validation.

Results To Date/Accomplishments

- Burner primary retrofit results:
  - Matching burner primary gas/fuel ratio or momentum ratio with air-fired operation produced a stable attached flame (good retrofit strategies).
  - Matching primary velocity with air-fired operation did not provide a stable attached flame (may depend on burner flexibility).
  - There is a fundamental difference in devolatilization rates and ignition between air and oxygen/FGR firing.
  - A stable flame can be achieved with no oxygen enrichment in the primary.
- Oxygen injection results:
  - Targeted oxygen injection at the burner primary-inner secondary boundary produced the most effective flame stabilization and ignition. Axial injection produced a permanently detached flame and radial injection produced a wider flame, but did not improve flame attachment.
  - Axial injection in the primary produced a more intensely radiating flame downstream of burner; secondary injection produced a less intense flame near the burner.
  - For maximum pre-mixed primary O_2, adding small amounts of oxygen enrichment radially through the bluff body did not improve flame attachment.
- Soot volume fraction ~40% lower for oxy-combustion cases than air-fired cases for the Utah coal, and 10–20% lower for PRB coal.
- NO_x emissions were up to 75% lower with oxy-combustion depending on level of staging.
- Corrosion testing results:
  - Waterwall (SA210) corrosion rates decreased when converting from air- to oxy-firing for all coals.
  - Superheater (T22, P91, and 347H) rates generally increased when converting from air- to oxy-firing.
  - 347H corrosion rates increased dramatically for SO_2 >~3,000 parts per million (ppm) and T_{probe}<~1,150 °F.
  - Corrosion for lower alloyed materials (T22, SA210) increased when changing between oxidizing-reducing. Likely to contribute to in-plant corrosion in near-burner and near-overfire air (OFA) port regions. Transient effects cannot be resolved using coupon tests.

- Mercury testing results:
  - Native mercury removal was higher for both OFC and L1500 cases.
  - Similar speciation for air- and oxy-firing; slightly lower total gas mercury under oxy conditions.

Next Steps

- Continue ash characterization and soot tests in laboratory-scale furnace.
- Validate and refine mechanisms (char oxidation, soot, slagging, fouling, corrosion); implement in CFD code.
- Design conceptual commercial-scale retrofit firing system.
- Assess oxy-combustion retrofit impacts on existing boiler.

Final test results will not be available until after the September 2011 project completion date.

Available Reports/Technical Papers/Presentations

General project information is available on the DOE/NETL website at: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/oxy-combustion/impacts.html

Andrew Fry, Bradley Adams, Dave Swensen and William Cox, "Potential Impacts of Oxy-Combustion Retrofit On Boiler Tube Corrosion Rate," AIChE Annual Meeting, Salt Lake City, UT, November 10, 2010.

Dunxi Yu, William Morris, Raphael Erickson, Jost O. L. Wendt, Andrew Fry and Constance Senior, "Ash Formation and Deposition During Oxy-Coal Combustion," AIChE Annual Meeting, Salt Lake City, UT, November 10, 2010.

M. Geier, C. R. Shaddix, and B. S. Haynes, "Oxy-Combustion of Pulverized Coal: Modeling of Char-Combustion Kinetics," 27th Annual International Pittsburgh Coal Conference, Istanbul, Turkey October 11–14, 2010.

Fry, A., Adams, B., Davis, K., Cremer, M., Swensen, D., Munson, S., Kazalski, P., Cox, W., Oryshchyn, D., Gerdemann, S., "Topics in Oxy-Coal Retrofit of Utility Boilers Burner Principles and Fire-Side Corrosion," The MEGA Symposium, August 30–September 2, 2010, Baltimore, MD.

"Characterization of Oxy-Combustion Impacts in Existing Coal-fired Boilers," Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, Pittsburgh, PA, September 2010. http://www.netl.doe.gov/publications/proceedings/10/co2capture/index.html

Fry, A., Adams, B., Cremer, M., Shan, J., "Development of Oxy-Burner Retrofit Principles for Existing Coal-Fired Utility Boilers," IEA 1st International Oxy-Fuel Combustion Conference, Cottbus, Germany, September 2009.

Adams, B., Fry, A., Senior, C., Wang, D., "Oxy-Combustion Impacts on Coal Ash Slagging and Fouling," IEA 1st International Oxy-Fuel Combustion Conference, Cottbus, Germany, September 2009.

Fry, A. and Adams, B., "Characterization and Prediction of Oxy-Combustion Impacts in Existing Coal-fired Boilers," 34th International Technical Conference on Clean Coal and Fuel Systems, Clearwater, FL, June 2009.

"Characterization of Oxy-Combustion Impacts in Existing Coal-Fired Boilers," NETL CO_2 Capture Technology for Existing Plants R&D Meeting, Pittsburgh, PA, March 2009.

NEAR-ZERO EMISSIONS OXY-COMBUSTION FLUE GAS PURIFICATION

Primary Project Goals

Praxair is developing a near-zero emission flue gas purification technology for a retrofitted existing coal-fired power plant with oxy-combustion technology.

Technical Goals

- Design a contaminant removal system that will produce saleable sulfuric acid and nitric acid without the need for flue gas desulfurization (FGD) or selective catalytic reduction (SCR) units.
- Design a second contaminant removal system that will produce gypsum.
- Achieve greater than 95% carbon dioxide (CO_2) capture by incorporating a vacuum pressure swing adsorption (VPSA) unit in an existing plant with a high air ingress, and reduce sulfur oxide (SO_x) and mercury (Hg) emissions by more than 99% and nitrogen oxide (NO_x) emissions by more than 90% (high and low sulfur coal).
- Perform a techno-economic study and an operability and integration evaluation to assess the commercial viability of retrofitting an existing power plant with the proposed technology.

Technical Content

Two approaches for SO_x/NO_x/Hg removal are proposed depending on the SO_x levels in the flue gas. By carrying out these unit operations at high pressure, it is envisioned that capital costs would be reduced while achieving low levels of SO_x and NO_x in the CO_2 stream. For plants with existing FGD and SCR, operating cost savings could be realized by shutting down those units while operating the proposed SO_x/NO_x removal process. For plants burning low sulfur coal, there is no need for investment in separate FGD and SCR equipment for producing high purity CO_2.

High air ingress in existing plants limits the amount of CO_2 that can be recovered from oxy-combustion flue gas using a cold box alone to <65%. The CO_2 recovery limitation is overcome by using a hybrid process that combines a cold box and VPSA (Figure 1). In the proposed hybrid process, up to 90% of CO_2 in the cold box vent stream is recovered by CO_2 VPSA and then recycled and mixed with the flue gas stream upstream of the compressor. The recovery from the process will be >95%.

Pollutant Removal

The high sulfur coal tests will be bench-scale and will utilize a single gas/liquid contact column that operates at up to 17 atm [250 pounds per square inch absolute (psia)] and 150 °C (300 °F) for testing multiple reactions. Nitric oxide (NO) in the flue gas is converted to nitrogen dioxide (NO_2), which catalyzes sulfur dioxide (SO_2) oxidation to sulfur trioxide (SO_3). The hydrolysis of SO_3 and NO_2 forms sulfuric and nitric acids.

The low sulfur coal experiments will use a single column unit [2.5 cm (1 inch) diameter, 3.8 cm (1.5 inch) long], and operate up to 17 atm (250 psia) and 93 °C (200 °F). Activated carbon is used as an adsorbent/catalyst for the capture of SO_x and NO_x from the flue gas. The activated carbon oxidizes the SO_2 to SO_3, NO to NO_2, and a periodic water wash will be used to remove the acids formed.

Technology Maturity:
Bench-scale, 5 kg of CO_2/hr

Project Focus:
Flue Gas Purification Options

Participant:
Praxair, Inc.

Project Number:
NT0005341

NETL Project Manager:
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Principal Investigator:
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Praxair, Inc.
minish_shah@praxair.com

Partners:
AES
Foster Wheeler
WorleyParsons Canada

Performance Period:
10/1/08 – 12/31/11

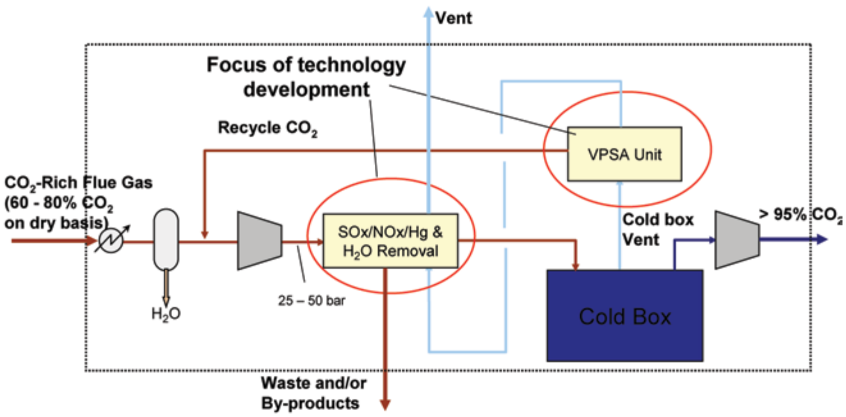

Figure 1: Technology Concept

The chemical reactions for the high and low sulfur coal pollutant removal system are summarized below.

High Sulfur Coal Reactions

$NO_2 + SO_2 \rightarrow NO + SO_3$

$NO + 1/2O_2 \rightarrow NO_2$

$SO_3 + H_2O \rightarrow H_2SO_4$

$NOx + H_2SO_4 \leftrightarrow H_2SO_4 \bullet NOx$

$3NO_2 + H_2O \rightarrow 2HNO_3 + NO$

Figure 2: High Sulfur Coal Pollutant Removal System

Low Sulfur Coal Reactions

$SO_2 + 1/2O_2 \rightarrow SO_3$

$NO + 1/2O_2 \rightarrow NO_2$

$SO_3 + H_2O \rightarrow H_2SO_4$

$3NO_2 + H_2O \rightarrow 2HNO_3 + NO$

Figure 3: Low Sulfur Coal Pollutant Removal

High CO_2 Recovery Using VPSA

The VPSA unit is a multi-bed unit that performs multiple depressurization/re-pressurizations steps. Oxy-combustion flue gas will enter the CO_2 VPSA from the “cold box” (25–35 atm and ambient temperature) that will recover additional CO_2 (produce 80–95% CO_2 concentration) and recycle the CO_2 back into the CO_2-rich flue gas stream at ambient pressure. The flue gas stream not recycled from the VPSA contains mainly oxygen (O_2), nitrogen (N_2), and argon (Ar) that will be vented to the atmosphere.

Technology Advantages

Cold box-VPSA hybrid technology achieves >95% CO_2 recovery even for plants with high air ingress. The flue gas purification process for high sulfur coal has lower capital and operating costs than FGD and SCR and it allows for revenue from sale of acids. The flue gas purification process for low sulfur coal will not need investment in expensive FGD and SCR units.

R&D Challenges

- Sulfuric acid process for SO_x/NO_x/Hg removal from high sulfur coal:
  - Reactor materials must be able to withstand the operating conditions in the process.
  - Determine an effective NO_x catalyst for producing saleable sulfuric acid.

- Activated carbon process for SO_x/NO_x/Hg removal from low sulfur coal:
  - Find activated carbon materials that are effective for regeneration based on sorption capacity and ability to maintain performance.
- Identify adsorbents with a tolerance to residual SO_x/NO_x to be used in the VPSA process.
- Determine VPSA cost benefit for recovering additional CO_2.
- Establish proper modifications required for retrofitting existing plants.

Results To Date/Accomplishments

Bench-scale experimental test systems have been built and commissioned for all three experimental programs.

- Sulfuric Acid Process:
  - Gas phase NO oxidation kinetics confirmed.
  - Greater than 98% NO_x absorption in one stage.
  - SO_x removal tests completed.
  - Removal of NO_x from sulfuric acid was not successful.
  - Sulfuric acid produced is not of commercial grade.
- Activated Carbon Process:
  - Two carbon materials selected based on SO_x removal screening tests.
  - Simultaneous SO_x/NO_x removal – SO_2 >99%, NO_x >96%.
  - Performance enhanced by lower temperature, higher pressure, and presence of moisture.
- High CO_2 Recovery Using VPSA:
  - Three adsorbents selected based on cost, CO_2 recovery, CO_2 purity, and vacuum pump.
  - Pilot unit with 12 vessels commissioned.
  - First data set meets/exceeds performance targets – 99% capture rate with VSPA and cold box.

Next Steps

- Complete long-term regenerability tests for activated carbon process.
- Build and operate a dual-bed continuous activated carbon process unit with 0.125 ton-per-day (tpd) capacity.
- Conduct bench-scale tests for VSPA SO_x/NO_x tolerance.
- Complete pilot-scale VSPA tests to find optimum combination of adsorbents and process configuration.
- Develop a simulation tool to predict VSPA process performance.
- Conduct a techno-economic analysis and operability assessment.

Final test results will not be available until the December 2011 project completion date.

Available Reports/Technical Papers/Presentations

Project webpage: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/oxy-combustion/near-zero.html

"Near-Zero Emissions Oxy-Combustion Flue Gas Purification" – Presentation given at the 2010 NETL CO_2 Capture Technology Meeting: http://www.netl.doe.gov/publications/proceedings/10/co2capture/presentations/tuesday/Minish%20Shah%20-%20NT0005341.pdf

"Near-Zero Emissions Oxy-Combustion Flue Gas Purification" – Fact Sheet: http://www.netl.doe.gov/publications/factsheets/project/Proj611.pdf

FLUE GAS PURIFICATION UTILIZING SO_X/NO_X REACTIONS DURING COMPRESSION OF CO_2 DERIVED FROM OXYFUEL COMBUSTION

Primary Project Goals

Air Products and Chemicals is designing and developing a system for purifying an oxy-combustion derived flue gas by utilizing the reactions of sulfur oxides (SO_x) and nitrogen oxides (NO_x) that occur during compression, leaving behind a pressurized, pure stream of carbon dioxide (CO_2).

Technical Goals

- Design and construct a 15-atm flue gas pilot development unit (PDU) for the removal of SO_x and NO_x from actual oxy-combustion derived CO_2-rich flue gas.
- Evaluate PDU performance based on effluents at different pressures and water recycle rates.
- Characterize the PDU effluents to asses any change in performance.
- Develop an engineering model to describe the 15-atm PDU performance.

Technical Content

Acidic gases must be removed from a CO_2 stream prior to pipeline transportation to avoid corrosion and to comply with purity requirements for applications such as enhanced oil recovery (EOR) and geological storage. In order to address this requirement, Air Products and Chemicals is developing a novel approach to remove SO_x and NO_x from the flue gas by converting them to sulfuric acid and nitric acid (HNO_3).

In order to determine the effect of pressure on sulfur dioxide (SO_2) and nitric oxide (NO) conversion, previous experiments were performed where one standard liter per minute (sl/min) of gas was supplied at both 8 and 15 atm. The results are shown in the Table 1.

Table 1: Pressure vs. Conversion

	15 atm			8 atm		
	Inlet	After Compressor and Receiver	Conversion	Inlet	After Compressor and Receiver	Conversion
ppm SO_2	900	20	98%	950	150	84%
ppm NO_x	500	50	90%	390	120	68%

Clearly, the conversion rate increases significantly with pressure. Therefore, it is logical to assume that these contaminants can be removed during the compression of CO_2.

The PDU developed for this project includes three main units, as indicated below: the scrubber/condenser, the compressor, and the reactor. Fine particulate ash and acid mist in the flue gas are removed prior to compression to avoid damage to the compressor.

Technology Maturity:

Pilot, flue gas, 2.45 tonnes CO_2/day

Project Focus:

Flue Gas Purification via Compression

Participant:

Air Products and Chemicals, Inc.

Project Number:

NT0005309

NETL Project Manager:

Timothy Fout
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Principal Investigator:

Kevin Fogash
Air Products and Chemicals, Inc.
fogashkb@airproducts.com

Partners:

None

Performance Period:

10/1/08 – 9/30/10

The compressor increases the pressure of the gas from near atmospheric to approximately 15 atm in a multistage adiabatic compressor unit. After the initial compression, the flue gas is cooled prior to entering the reactor. In the reactor, the flue gas is contacted with water to obtain complete conversion of SO_2 to sulfuric acid and high conversion of NO_x to HNO_3.

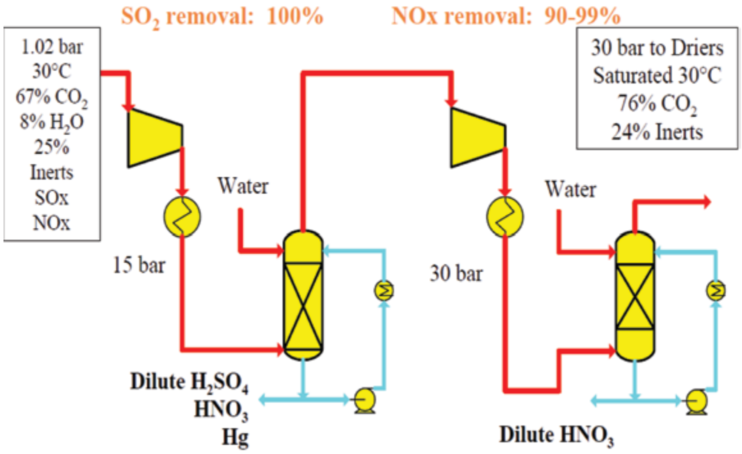

Figure 1: Flue Gas Pilot Development Unit (PDU)

Multiple tests were conducted within two campaigns of the project. The host site was Alstom Power's 15-MW_{th} oxy-combustion pilot unit. The 15-bar reactor system received a slip stream of 0.25–0.33 MW_{th} equivalent flow rate from the Alstom unit for several days. A variety of process conditions were tested, including changes in SO_x and NO_x feed levels, to enable a broad understanding of the technology. The flue gas PDU is shown in Figure 2. In the reactor, the flue gas was contacted with water to obtain up to complete conversion of SO_2 to sulfuric acid and high conversion of the NO_x to HNO_3. Figure 3 shows an example of the results obtained.

Figure 2: PDU at the Host Site

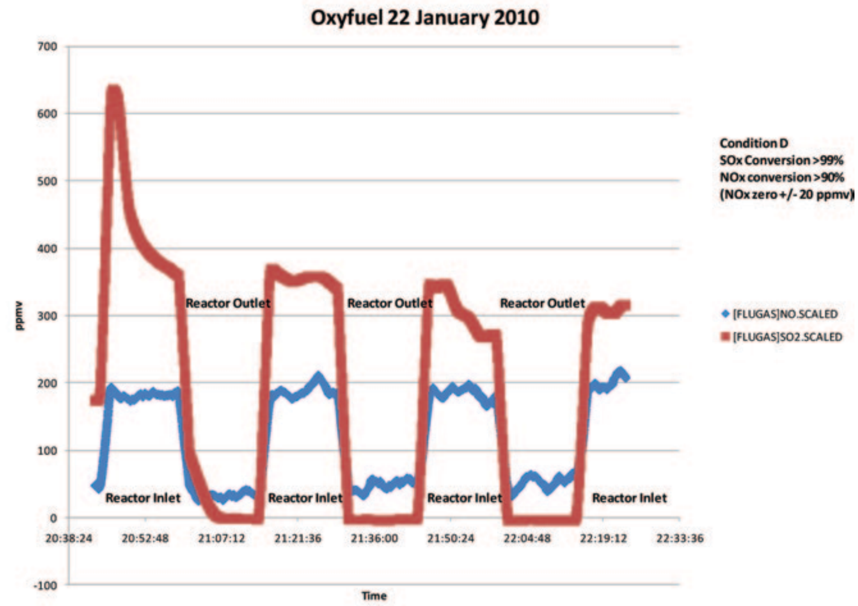

Figure 3: Example Results from the Oxyfuel Test

Technology Advantages

By incorporating an efficient NO_x and SO_x removal system with a compressor, the need for low NO_x burners, flue gas desulfurization (FGD), and post-combustion NO_x control systems are greatly reduced or eliminated for oxy-combustion plants. In particular, this system allows for a degree of freedom to optimize any upstream purification needs and target reduction in size or removal of upstream equipment for the retrofit of an existing plant or the construction of a new plant.

R&D Challenges

The main challenge is to obtain sufficient data for engineering design and to further develop the understanding of the effect of residence time, pressure, and temperature on the unit performance. The prolonged presence of acid gases in the system and the presence of such gases at high pressures in the compressor may lead to the requirement of more advanced materials of construction.

Results To Date/Accomplishments

- Developed a simulation of the flue gas PDU and modeled the reactions occurring within the reactor.
- Conducted simulations to understand the influence of liquid to vapor flow rates on SO_2 and NO_2 conversions as well as overall residence time in the reactor.
- Developed a design specification for the PDU and auxiliary equipment.
- Completed construction and installed the PDU at host site.
- For the overall process, total SO_2 removal was 40–100% (based on gas compositions).
- For the overall process, total NO_x removal was 60–90% (based on gas compositions).
- The effects of variations in the SO_2/NO_x feed ratio, column pressure, gas flow rate, and liquid recirculation on the reactor performance were elucidated. Process performance was most sensitive to SO_2/NO_x feed ratio, over the range of parameter values investigated.

- SO_2 was removed from the flue gas through both sulfite and sulfate mechanisms.
- No evidence of NO_x removal was observed prior to compression, confirming that elevated pressure was required to accelerate the oxidation reaction of NO to NO_2 to a rate at which appreciable NO_x removal (as HNO_3) could be achieved.

Next Steps

Project complete.

Available Reports/Technical Papers/Presentations

Project webpage: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/oxy-combustion/purification.html

"Flue Gas Purification Utilizing SO_x/NO_x Reactions During Compression of CO_2 Derived from Oxyfuel Combustion." Presentation given at the 2010 NETL CO_2 Capture Technology Meeting. http://www.netl.doe.gov/publications/proceedings/10/co2capture/presentations/tuesday/Kevin%20Fogash%20-%20NT0005309.pdf

Fact Sheet. "Flue Gas Purification Utilizing SO_x/NO_x Reactions During Compression of CO_2 Derived from Oxyfuel Combustion." http://www.netl.doe.gov/publications/factsheets/project/Proj595.pdf

"Purification of Oxyfuel-Derived CO_2 for Sequestration or EOR," Technical paper presented at the 8th International Conference on Greenhouse Gas Control Technologies in Trondheim, Norway. http://www.netl.doe.gov/technologies/coalpower/ewr/co2/pubs/5309%20Air%20Products%20oxy-combustion%20GHGT-8%20paper.pdf

JUPITER OXY-COMBUSTION AND INTEGRATED POLLUTANT REMOVAL RESEARCH AND DEVELOPMENT TEST FACILITY

Primary Project Goals

Jupiter Oxygen will design, construct, and operate a 5-MWe, high flame temperature, oxy-combustion test facility with a 20-kWe integrated pollutant removal (IPR) bench-scale system to demonstrate carbon dioxide (CO_2) capture from an oxy-combustion process.

Technical Goals

- Develop high flame temperature oxy-fuel burners.
- Retrofit an existing boiler with high flame temperature oxy-combustion and operate with coal and natural gas without altering interior boiler materials.
- Collect data on burner performance and boiler heat transfer.
- Conduct a study of the ash and slagging characteristics of the process and its impact on boiler materials.
- Capture CO_2 and collect data on impurity removal using the Jupiter Oxygen combustion process along with IPR technology developed by NETL.
- Evaluate the high flame temperature approach with respect to capital and operating costs.
- Design, build, and test a new 1-MW_{th} module boiler design for high flame temperature oxy-combustion.

Technical Content

There are two different approaches to oxy-combustion. Jupiter's approach is to use a high temperature flame that is minimally tempered with nitrogen, CO_2, or other inert gases (the only tempering occurs as a result of flue gas recycle that is used to motivate coal). High flame temperature oxy-combustion results in improved heat transfer in the boiler's radiant zone. Other oxy-combustion facilities use a low flame temperature approach which uses large amounts of CO_2 recycled through or at the burner to cool the flame to a temperature similar to air firing. The unique combination of the high-temperature approach coupled with the IPR system will allow the evaluation of the impact of using high- and low-temperature approaches and energy recovery on a variety of aspects of power plant operations.

Coal analyses, such as heating value, mineralogy, and trace element content; proximate; and ultimate analyses will be determined using ASTM procedures. This information will be used to determine the effect of the coal characteristics on oxy-combustion performance and the effectiveness of emissions capture. Other performance measurements for the test facility include water tube and web temperature, heat transfer rate, flue gas emissions [nitrogen oxides (NO_x), carbon monoxide (CO), CO_2, sulfur dioxide (SO_2), and trace metals], and loss on ignition (LOI) of the ash. The facility will incorporate the following approaches to conduct measurements:

Technology Maturity:
Pilot/bench

Project Focus:
Oxy-Combustion and Integrated Pollutant Removal

Participant:
Jupiter Oxygen Corporation

Project Number:
NT42811

NETL Project Manager:
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Principal Investigator:
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Jupiter Oxygen Corporation
m_schoenfield@jupiteroxygen.com

Partners:
Coalteck, LLC
Doosan Babcock, LLC
EPRI
Maxon Corporation
Michigan State University
Purdue University
University of Wyoming

Performance Period:
9/28/06 – 9/30/11

- Flue gas species concentrations will be measured by Fourier Transform Infrared Spectroscopy (FTIR).
- Ash LOI will be measured by laboratory testing.
- Heat transfer in the radiant zone will be determined by spectral flame mapping, furnace gas temperature measurement (at the screen wall and boiler exit), temperature measurements of the flux through the boiler tubes, and optical measurements of the total radiant heat flux from the flame.
- Flame shape and transient behavior will be evaluated by high-speed video.
- Net heat output from the burner and heat absorbed by the boiler will be calculated based on combustion and steam side energy balances.
- Combustion side mass balances will be calculated by combining species measurements with mass flows.
- Corrosion monitoring probes will be used.
- Gas-phase and particulate-phase trace elements, including mercury (Hg), will be measured in samples from select runs.
- IPR contaminant removal will be measured by laboratory analyses and FTIR.

The IPR system was added to the pilot facility to remove pollutants from the oxy-combustion flue gas re-circulated stream. The current device is used to process 45 kg/hr (100 lb/hr) of flue gas from the facility. The IPR system will capture, separate, and produce a dry, supercritical stream of CO_2; a stream of captured pollutants; and a stream of condensed water from the flue gas. Figure 1 shows a representation of major components of a typical IPR system.

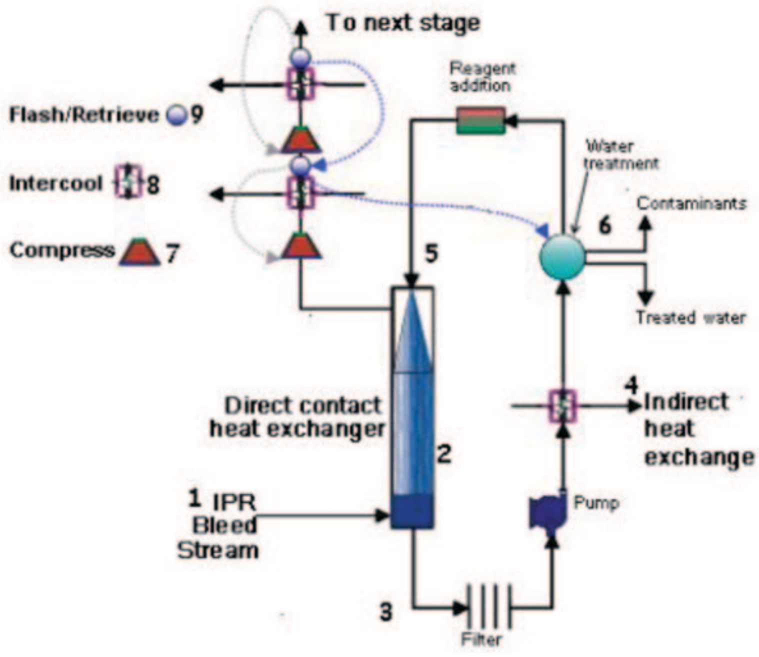

Figure 1: Representation of IPR System Integrated at a Pilot-Scale Facility

The generalized IPR process flow diagram is presented above: a flue gas bleed stream (1) enters the IPR system into a glass-pipe spray tower (2) in which sulfur oxide (SO_x) is removed by a spray stream (reagent addition) as the gas rises. The spray water and combustion condensed water (3) are cooled (4) and partially re-circulated back into the spray tower (5). The water that is not re-circulated back in to the spray tower is treated outside the IPR system (6). As the scrubbed gas leaves the tower, it enters a two-stage reciprocal compressor (7) and a water-cooled, counter flow heat exchanger (8). During the compression stage, separated water can be collected in the collection vessel (9).

Technology Advantages

The higher flame temperature improves heat transfer in the radiant zone, which increases boiler efficiency. Oxyfuel combustion lowers the quantity of flue gas, concentrates CO_2 in the flue gas, and significantly reduces NO_x emissions. For retrofit applications, this technology maintains actual water wall and steam temperatures without altering the boiler design or size. For new construction this technology can use a smaller boiler, which provides the same thermal output as larger, existing power plant boilers.

R&D Challenges

Design, build, and test a new, 1-MW_{th} module boiler design for high flame temperature oxy-combustion.

Results To Date/Accomplishments

- Retrofitted and operated a 5-MWe equivalent air-fired boiler as an oxy-coal combustion test facility without major boiler modifications. The test facility was operated along with ancillary systems including oxygen production and generated appropriate steam.
- Performed a series of oxy-coal burner development tests which resulted in a modified first generation burner.
- Performed parametric studies with the modified first generation oxy-coal burner.
- No increased fouling, slagging, or damage to boiler materials indicated.
- Developed a computational fluid dynamics (CFD) model of the modified first generation burner.
- Designed, constructed, and operated a 20-kWe equivalent IPR facility.
  - Demonstrated CO_2 capture at 95–100%.
  - 95% NO_x, SO_x, and particulate removal; 60–90% Hg removal.
  - $FeCl_3$/polymer pairing found to be effective flue gas condensate flocculent.
- Full-scale parametric model of a power plant retrofitted with high temperature oxy-combustion and an IPR system has been developed and is ready for economic evaluation.

Next Steps

- Develop second generation oxy-coal burner based on CFD modeling and first generation testing designed for improved coal/oxygen mixing, shorter flame length, and turndown capability.
- Improve flame characterization and heat transfer measurement.
- Develop an air-coal performance baseline for the test facility.
- Conduct IPR system performance tests and modeling to optimize heat recovery and gas reactions.
- Evaluate interactions between gas species that are expected to enhance the removal of SO_x, NO_x, and Hg.
- Complete slagging, fouling, and corrosion studies.
- Conduct analysis for technical and economic scale up of the technologies.

Final test results will not be available until the September 2011 project completion date.

Available Reports/Technical Papers/Presentations

Project webpage: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/oxy-combustion/jupiter.html

Oxy-Fuel Burner and Integrated Pollutant Removal Research and Development Test Facility – Presentation given at the 2010 NETL CO_2 Capture Technology Meeting: http://www.netl.doe.gov/publications/proceedings/10/co2capture/presentations/tuesday/Manny%20Menendez%20-%20NT42811.pdf

Project update report (Aug 2010): http://www.netl.doe.gov/technologies/coalpower/ewr/co2/pubs/42811_ProjectUpdate_0810.pdf

Project topical report (Aug 2009): http://www.netl.doe.gov/technologies/coalpower/ewr/co2/pubs/42811%20Jupiter%20topical%20August%202009.pdf

Technical paper from the Proceedings of the 34th International Technical Conference on Coal Utilization and Fuel Systems (Jun 2009): http://www.netl.doe.gov/technologies/coalpower/ewr/co2/pubs/42811%20Jupiter%20paper%20Clearwater%20jun09.pdf

S. Gerdemann, C. Summers, D. Oryshchyn, B. Patrick, T. Ochs, "Developments in Integrated Pollutant Removal for Low-Emission Oxy-Fuel Combustion."

Jupiter Oxycombustion and Integrated Pollutant Removal of the Existing Coal-Fired Power Generation Fleet – CO_2 Capture Technology for Existing Plants R&D Meeting – March 2009.

Results of initial operation of the Jupiter Oxygen Corporation oxyfuel 15 MW_{th} *burner test facility* – Paper presented at GHGT-9 Conference – November 2008. http://www.netl.doe.gov/technologies/coalpower/ewr/co2/pubs/Nov%202008%20GHGT9%20JOC%20%26%20NETL%20Results%20of%20Initial%20Operation%20of%20th.pdf

The Jupiter Oxygen Boiler Test Facility: 3rd *Generation* – Poster presented at GHGT-9 Conference – November 2008. http://www.netl.doe.gov/technologies/coalpower/ewr/co2/pubs/2008%20JOC%20GHGT9%20poster.pdf

Project Status Update. January 2009. http://www.netl.doe.gov/technologies/coalpower/ewr/co2/pubs/42811 WEB UPDATE Jan 2009.pdf

DEVELOPMENT OF COST-EFFECTIVE OXY-COMBUSTION TECHNOLOGY FOR RETROFITTING COAL-FIRED BOILERS

Primary Project Goals

Babcock and Wilcox (B&W) is developing oxy-combustion technology for application to new and existing cyclone and wall-fired boilers. A two-phase research project is being conducted that includes pilot-scale testing and a full-scale engineering and economic analysis.

Technical Goals

- Conduct pilot-scale testing to evaluate the effect of coal rank (i.e., bituminous, subbituminous, and lignite) on oxy-combustion boiler operation.
- Determine the equipment requirements for the boiler island, flue gas purification, carbon dioxide (CO_2) compression, CO_2 transportation, and CO_2 sequestration for different coal ranks and boiler designs.
- Investigate the potential for multi-pollutant [nitrogen oxides (NO_x), sulfur dioxide (SO_2), and particulate] emissions control.
- Validate an existing three-dimensional computational flow, heat transfer, and combustion model for oxy-combustion scale up to a commercial-size boiler.
- Conduct an engineering and economic assessment of the technology for commercial-scale retrofit and green field application for cyclone and wall-fired boilers.
- Assess CO_2 capture cost reductions via energy integration of the air separation unit (ASU), flue gas purification, and CO_2 compression systems.
- Evaluate the impact of oxy-combustion implementation on net power production and cost of electricity (COE) for cyclone and wall-fired boilers.

Technical Content

B&W had previously conducted pilot-scale oxy-combustion testing for wall-firing at 1.8 and 30 MW_{th}. In this project, a pilot-scale evaluation—14 GJ/hr (6 million Btu/hr)—is conducted for three coals using a cyclone boiler configuration at its Barberton, OH, test facility. An illustration of the oxy-combustion pilot-scale test facility is shown below (Figure 1). The three types of coal tested are North Dakota lignite, Western sub-bituminous, and Eastern bituminous. Each of the oxy-combustion tests is run for 100 continuous hours to assess the slagging, fouling, heat transfer, and overall operability characteristics. Data from the pilot-scale testing is used to validate a computational fluid dynamic (CFD) model of the oxy-combustion process. From the test data, equipment required for flue gas purification, compression, transportation, and sequestration is determined for the engineering and economic assessment.

Technology Maturity:

Pilot-scale laboratory testing using actual flue gas; equivalent to 13 tons of CO_2/day

Project Focus:

Oxy-Combustion for Cyclone and Wall-Fired Boilers

Project Developer:

Babcock & Wilcox

Project Number:

NT42747

NETL Project Manager:

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Partners:

Air Liquide
Battelle

Performance Period:

4/1/06 – 12/31/10

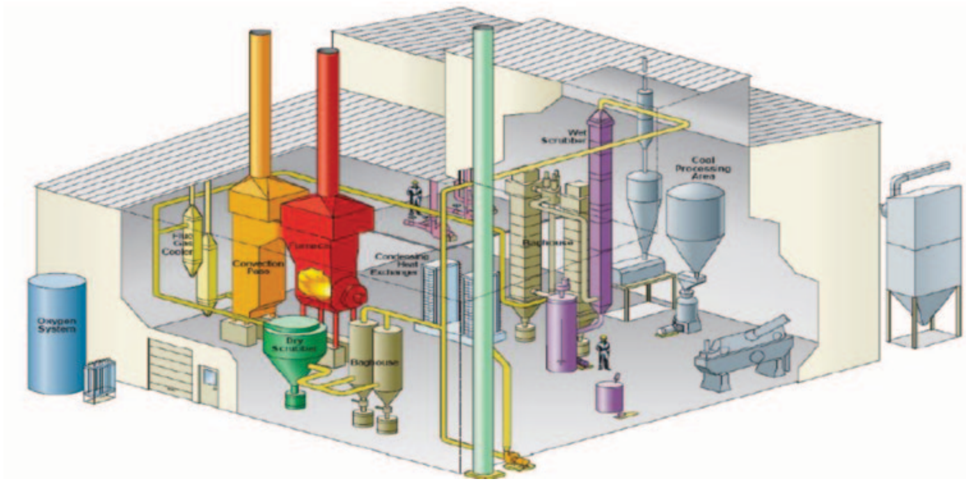

Figure 1: Illustration of B&W's Oxy-Combustion Pilot-Scale Test Facility in Barberton, Ohio

A modeling assessment is also being conducted to compare three CO_2 capture purification processes: (1) no purification—only drying to Kinder Morgan pipeline specifications with water (H_2O) at 600 parts per million volume (ppmv); (2) partial condensation at cryogenic conditions (cold box)—95% CO_2 purity target; and (3) cold box including distillation—1 ppm oxygen (O_2) target. The purification assessment includes investigation of operating costs, energy requirements, and effects of air infiltration. The following graph (Figure 2) represents a model analysis showing the effect of purification process on CO_2 recovery, purity, and specific energy.

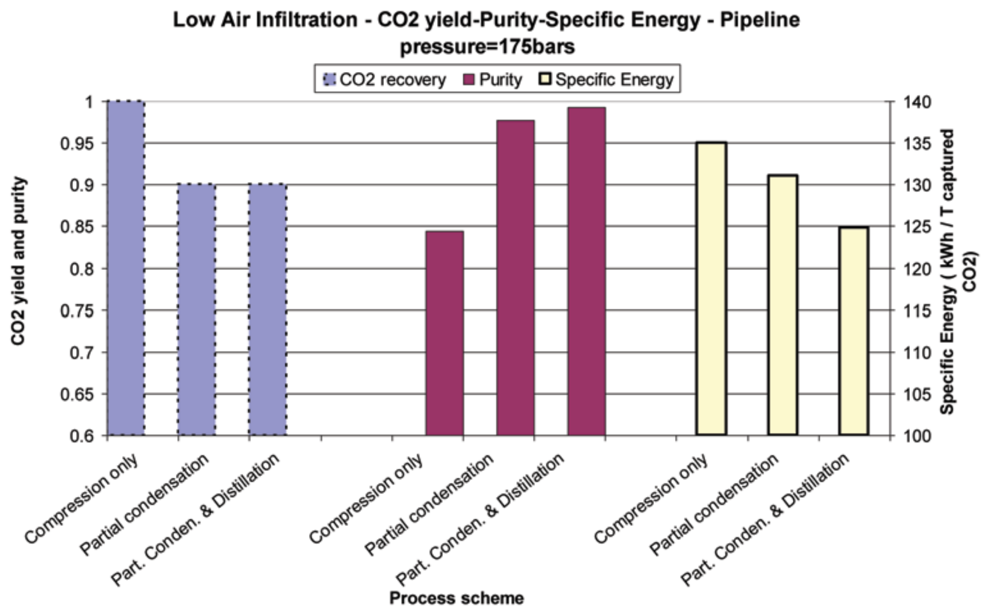

Figure 2: Model Analysis Showing Effect of Purification Process on CO_2 Recovery, Purity, and Specific Energy

Technology Advantages

Oxy-combustion has the potential to offer a lower cost solution for CO_2 capture compared to post-combustion CO_2 capture technologies.

R&D Challenges

The necessary level of flue gas purification remains an issue regarding potential adverse impacts on CO_2 transportation and storage:

- Potential precipitation problems with SO_2 forming sulfate minerals (e.g., anhydrite) if high-sulfur coal is used without scrubbing.
- Non-condensable gases, such as nitrogen (N_2) and O_2, could affect subsurface processes which might require more purification. For example, non-condensable gases could create multi-phase flow, which can reduce injectivity or the capacity of the storage site.

Results To Date/Accomplishments

- Completed oxy-combustion pilot-scale testing with the following general results:
    - Oxy-combustion is a technically feasible technology for wall-fired and cyclone boilers.
    - The flame stability and cyclone slagging characteristics was not negatively impacted by oxy-combustion.
    - Boiler emissions [NO_x, carbon monoxide (CO), and unburned combustibles] are lower for oxy-combustion than air-firing.
    - Radiant boiler and convection pass heat absorptions under optimum oxy-combustion conditions was similar to air-firing.
    - Higher CO_2 (up to 90%) levels were achieved when air leakage was minimized by reducing pressure drop in the boiler back-end equipment.
    - Sulfur dioxide must be scrubbed from recycle gas for high-sulfur coal applications to maintain acceptable boiler corrosion.
    - Higher sulfur trioxide (SO_3) concentrations occur with oxy-combustion than air-firing at the convection pass exit that could increase corrosion if the flue gas temperature goes below acid dew point.
- Completed engineering feasibility and economic analysis with the following general results:
    - Co-sequestration of CO_2 and SO_2 might be feasible in deep geological reservoirs. It was concluded that the pipeline transportation corrosion by acid gas can be minimized by removing the moisture from the flue gas.
    - Modeling of the compression and purification unit (CPU) demonstrated that the overall energy requirement is lower if flue gas inerts are removed in the CPU than compressing the entire flue gas for pipeline transport.
    - Oxy-combustion is an economically viable technology. The incremental cost of oxy-combustion for existing boilers varied between $0.05 and $0.07/kWh, which is competitive with other technologies.
    - COE for green-field boilers using oxy-combustion coupled with ultra-supercritical boilers was 25% higher than COE for a supercritical boiler under air-firing without CO_2 capture, which is below the DOE/NETL target of 35%.
    - Oxy-combustion can be applied to the majority of the existing wall-fired and cyclone boilers depending on space and existing equipment. The site requirements are similar to those for post-combustion capture.

Next Steps

Project completed December 2010. Final technical report under review.

Available Reports/Technical Papers/Presentations

General project information is available on the DOE/NETL website at: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/oxy-combustion/oxy-combustion.html

"Development of Cost Effective Oxy-Combustion for Retrofitting Coal-Fired Boilers," Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, Pittsburgh, PA, September 2010. http://www.netl.doe.gov/publications/proceedings/10/co2capture/index.html

"Development of Cost Effective Oxy-Combustion for Retrofitting Coal-Fired Boilers," NETL CO_2 Capture Technology for Existing Plants R&D meeting in Pittsburgh, PA, March 2009.

"Considerations for Treating Impurities in Oxy-Combustion Flue Gas Prior to Sequestration," 9th International Conference on Greenhouse Gas Control Technologies in Washington, DC, Nov. 2008.

"Developing Oxy-combustion for Retrofitting Coal-fired Boilers," 7th Annual Conference on Carbon Capture and Sequestration in Pittsburgh, PA, May 2008.

"Development of Cost Effective Oxy-Combustion Technology for Retrofitting Coal-Fired Boilers," NETL Fact Sheet.

OXY-FUEL TURBOMACHINERY DEVELOPMENT FOR ENERGY-INTENSIVE INDUSTRIAL APPLICATIONS

Primary Project Goals

Clean Energy Systems (CES) is designing and developing a pre-commercial oxy-fuel (O-F) combustor, able to utilize synthesis gas (syngas), which will be used in a power generation cycle able to achieve high thermal efficiency with near-zero atmospheric emissions, including carbon dioxide (CO_2). The technology is a high-pressure O-F combustor that produces a steam/CO_2 working fluid for expansion in a turbine.

CES is also designing and developing a commercial-scale O-F turbine that can be deployed in industrial O-F plants that capture >99% of the produced CO_2, at competitive cycle efficiency and cost-of-electricity, using diverse fuels including gasified petcoke/coal, gasified or liquefied renewable fuels, and natural gas (NG).

Technical Goals

- Develop a detailed design of a 100 megawatt thermal (MW_{th}) O-F syngas combustor.
- Develop a detailed design and test an O-F reheat (RH) combustor. The RH combustor is a variant of the main O-F combustor and enables the exhaust from a high-pressure turbine to be reheated to the higher and more efficient inlet temperatures of an O-F intermediate pressure turbine (IPT).
- Develop a detailed design of a commercial-scale O-F turbine.
- Fabricate an O-F combustor with an attendant control system.
- Fabricate an O-F IPT with a control system integrated with an O-F combustor.
- Commission and test the O-F combustor using NG.
- Integrate, commission, and test O-F IPT with an O-F combustor using NG.
- Conduct pilot-scale testing of alternative fuels (syngases, petcoke, glycerol, etc.).

Technical Content

CES has designed a pre-commercial O-F combustor that can utilize syngas in an O-F power cycle to produce electricity from fossil fuel at high-thermal efficiency with near-zero emissions. The CES O-F combustor can produce high-pressure drive gases at temperatures between 315 and 1,760 °C (600–3,200 °F).

The CES cycle involves burning high purity oxygen (O_2) with a gaseous carbonaceous fuel (NG, coal syngas, gasified biomass, etc.) in the presence of water to generate a high-pressure, high-temperature drive gas comprised of approximately 90 vol% steam and 10 vol% CO_2 (when combusting NG), or 75 vol% steam and 25 vol% CO_2 (when combusting syngas). The drive gas powers steam or aero-derivative turbo-generators to produce electricity.

Technology Maturity:

100 MW thermal-scale oxy-fuel combustor and turbine

Project Focus:

Oxy-Syngas Combustor

Project Developer:

Clean Energy Systems, Inc.

Project Number:

NT42645

NETL Project Manager:

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Principal Investigator:

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Partners:

Florida Turbine Technologies, Inc.
Siemens Energy, Inc.

Performance Period:

10/1/05 – 9/30/14

The heart of the O-F combustor is the main injector, which is used to inject precisely controlled quantities of O_2, fuel, and water into the combustion chamber. Figure 1 depicts the assembled syngas combustor with the main O_2/fuel/water injector assembly at the left end of the combustor.

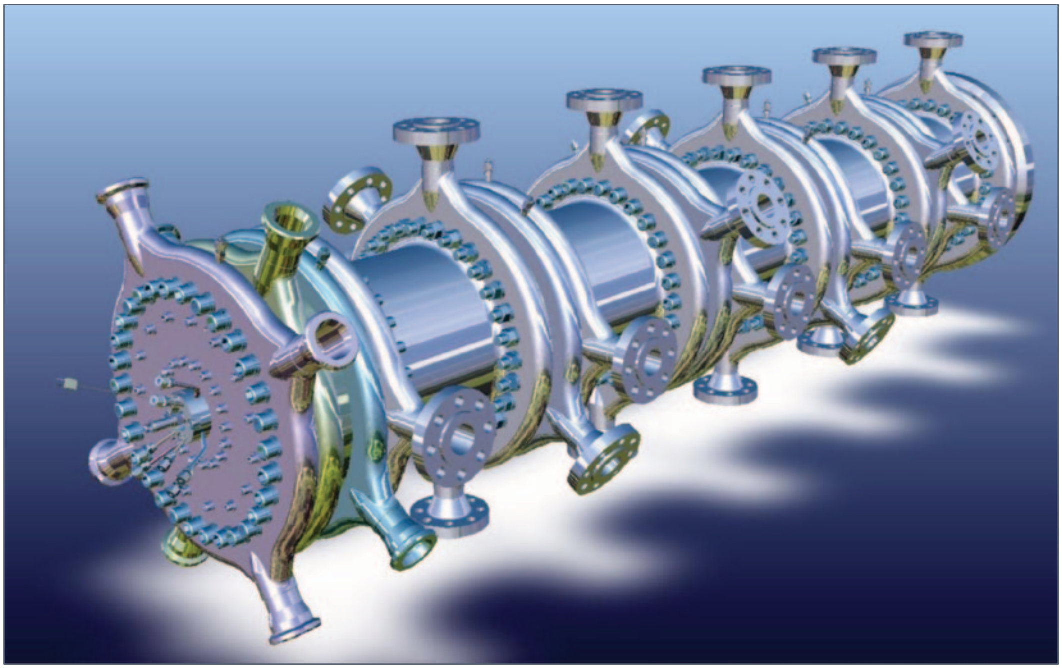

Figure 1: Syngas O-F Combustor Assembly

To utilize the high drive gas temperatures, and thereby achieve significantly higher plant efficiencies, CES is also working with turbine developers to accelerate deployment of advanced, high-temperature O-F IPTs. These commercial-scale IPTs are derived from existing high-temperature gas turbines. The gas turbines are being modified to utilize the steam-CO_2 drive gas from the CES O-F combustor and will incorporate unique O-F RH combustors to boost the inlet steam/CO_2 temperature, improving overall plant efficiency by up to 10%. This approach fields high-temperature steam turbines faster and less expensively by utilizing gas turbines already capable of high inlet temperatures. In a two-phased approach, CES first modified an aero-derivative aircraft turbine (J79) to accept the steam/CO_2 drive gas by removing its compressor, quadrupling its potential electrical power output. In a joint effort with Florida Turbine Technologies (FTT), an existing J79 turbine combustor "can" was modified to an O-F RH combustor configuration and hot-fired to confirm FTT modeling predictions of temperature and pressure profiles. Figure 2 is a cutaway view of a single-can J79 RH combustor.

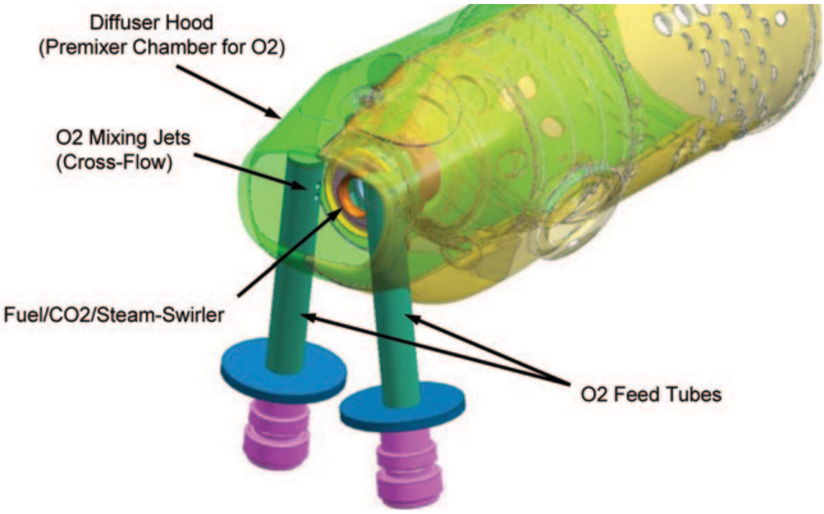

Figure 2: Cutaway Image of J79 Oxy-Fuel Combustor

The second phase of O-F turbine development is the re-engineering of a commercial-scale gas turbine, the 50-MWe Siemens SGT-900, to an O-F IPT (OFT-900) capable of tripling the original turbine's power output by up to 150 MWe. FTT, under contract to CES, is re-engineering the SGT-900 and will provide detailed manufacturing drawings for the conversion to an OFT-900. Siemens Energy will then manufacture and install the new O-F IPT components on a refurbished SGT-900. The converted IPT will then be tested at low power at CES's test facility. Figure 3 shows a conceptual drawing of the OFT-900; a section of the top casing removed to show interior detail.

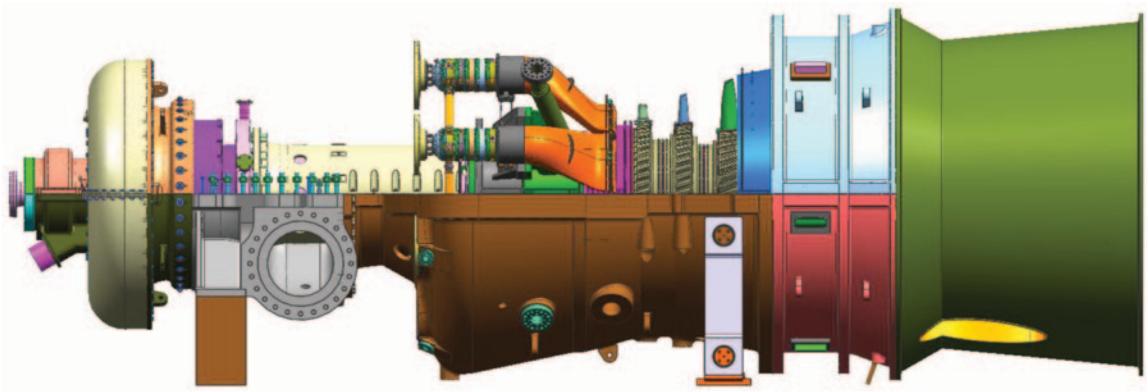

Figure 3: OFT-900 Concept Drawing (Top Casing Removed to Show Detail)

In support of the OFT IPT design, CES is conducting a parallel development of two O-F RH combustor designs, an aero-derivative approach led by the FTT development team, and a platelet-style design by CES engineers who developed the main O-F combustor. A half-annulus of the CES-style OFT-900 RH combustor is shown in Figure 4, with transitions to turbine inlet.

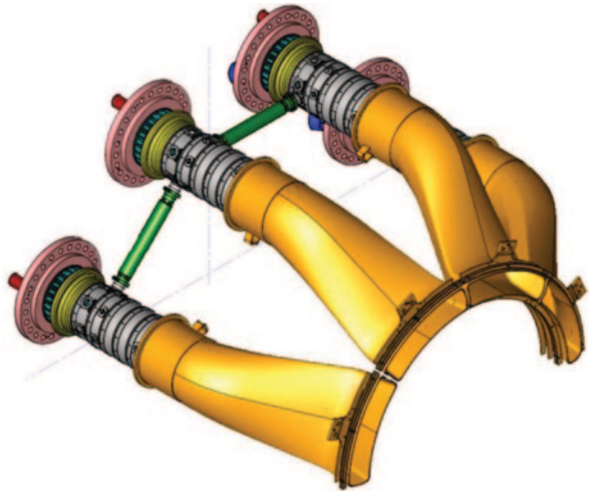

Figure 4: CES RH Combustor Concept with Cross-Fire Tubes and Transition Duct to O-F Turbine Inlet

CES will upgrade its test facility as necessary to support OFT-900 testing, while Siemens fabricates the OFT-900. The OFT will be installed at the test site and integrated with CES's main O-F combustor. After the turbine and its support systems are commissioned, approximately one year of integrated testing of the OFT-900 and O-F combustor will be conducted.

Technology Advantages

O-F Combustor:

An O-F combustor can burn a variety of fossil and renewable fuels to produce a drive gas consisting of steam and readily separable CO_2. This process (the CES cycle) yields a base-load power cycle that captures virtually 100% the CO_2 emissions through condensation of the steam from the effluent. In addition, the high-temperature drive gas produced by the O-F combustor enables higher-efficiency power cycles when coupled with high-temperature turbines.

High Temperature Turbine:

The capabilities of advanced, high-temperature turbines [up to 1,204 °C (2,200 °F)] permits plant heat rate improvements of 25% compared to conventional steam turbines. By utilizing modified gas turbines as O-F IPTs, development schedules and costs are significantly reduced, allowing accelerated deployment of high-temperature, O-F compatible steam turbo-generators to the market.

R&D Challenges

High Temperatures:

Equipment is subjected to increased stress, potentially increasing maintenance/ reducing life cycles.

Steam/CO_2 Drive Gas:

Condensate from steam/CO_2 drive gases is acidic (carbonic acid), requiring the use of costlier, corrosion-resistant materials. Also, steam/CO_2 transfers heat to metal surfaces more readily than the drive gases from air-fuel combustion, requiring provision for more effective cooling, including use of steam and/or CO_2 as a cooling medium instead of air.

Results To Date/Accomplishments

- Completed a detailed design of a 100 MW_{th} oxy-syngas combustor and its enclosure. In parallel, built mirror-image 170 MW_{th} NG-fired O-F combustor, commissioned unit, and began hot-fire testing. Ignition tests and low-power operations conducted to-date with good results. Lessons learned applied to syngas combustor enclosure design.
- Completed hot-fire testing of the J79 O-F RH combustor. FTT modeling showed excellent correlation with cold-flow testing, though discrepancies between predictions and results occurred during hot-fire tests. FTT has updated its combustor model to reflect test results—the revised combustor model will be used in designing the O-F reheaters for the OFT-900. J79 O-F RH combustor had ignition difficulties due to poor mixing of reactants, but combustor ran well after ignition, showing good turn-down capabilities and resistance to flame out.
- Completed design of CES's platelet O-F RH combustor. This design is the first of two OFT-900 RH combustor alternatives. CES design is undergoing computational fluid dynamics (CFD) analysis to verify uniform mixing and desired exhaust temperature profiles, and minimal pressure losses are achieved before being released for manufacture.
- Completed engineering design of the O-F IPT assemblies, excepting the O-F RH combustor. FTT engineering activities are now focused on completing FTT's O-F RH combustor design (second RH combustor design alternative), life modeling of the O-F turbine, and completion of individual assembly drawings.
- Purchased used SGT-900 for conversion to OFT-900.

Next Steps

- Submit CES drawing packages for 100 MW_{th} O-F syngas combustor, enclosure/piping drawings, and enclosure technical specification.
- Complete detailed manufacturing drawings for OFT-900 assemblies.
- Complete analyses and detailed engineering drawings for both FTT and CES OFT-900 O-F RH designs.
- Removal and shipment of SGT-900 to Siemens facility for refurbishment.
- Award contract(s) for subsystem modifications required to upgrade test facility to accommodate O-F combustor and OFT-900 operations.
- Determine fuels and develop test plan for pilot-scale alternative fuels testing with a CES O-F combustor.

Available Reports/Technical Papers/Presentations

Anderson, R., Viteri, F., Hollis, R., Keating, A., Shipper, J., Merrill, G., Schillig, C. Shinde, S., Downs, J., Davies, D., and Harris, M., 2010, "Oxy-Fuel Gas Turbine, Gas Generator and Reheat Combustor Technology Development and Demonstration," ASME Paper No. GT2010-23001.

Anderson, R., Viteri, F., Hollis, R., Hebbar, M., Downs, J., Davies, D., and Harris, M., 2009, "Application of Existing Turbomachinery for Zero Emissions Oxy-Fuel Power Systems," ASME Paper No. GT2009-59995.

Anderson, R., MacAdam, S., Viteri, F., Davies, D., Downs, J., and Paliszewski, A., 2008, "Adapting Gas Turbines to Zero Emission Oxy-Fuel Power Plants," ASME Paper No. GT2008-51377.

Hustad, C., 2008, "Development of Low and Zero Emission Fossil Fuel Power Generation in Emerging Niche Markets," ASME Paper No. GT2008-50106.

Keating, A., "Alternative Synthetic Fuels Injector Tests," EISG Report on Project EISG 04–10, California Energy Commission Grant #54085A, July 2007.

Pronske, K., Trowsdale, L., MacAdam, S., Viteri, F., Bevc, F., and Horazak, D., 2006, "*Overview of Turbine and Combustor Development for Coal-Based Oxy-Syngas Systems*," ASME Paper No. GT2006-90816.

Anderson, R., Baxter, E. and Doyle, S., "Fabricate and Test an Advanced Non-Polluting Turbine Drive Gas Generator," Final Report under DE Cooperative Agreement No. DE-FC26-00NT 40804, 1 September 2000 to 1 June 2003.

Anderson, R., "Development of a Unique Gas Generator for a Non-Polluting Power Plant," EISG Report on Project EISG 99-20, California Energy Commission Grant #99-20, May 2001.

OXYGEN-FIRED CO_2 RECYCLE FOR APPLICATION TO DIRECT CO_2 CAPTURE FROM COAL-FIRED POWER PLANTS

Primary Project Goals

Southern Research Institute (SRI) is designing and developing carbon dioxide (CO_2) recycle technology for oxy-combustion retrofit applications.

Technical Goals

The technical goals of this project are to:

- Modify the 1-MW_{th} pilot-scale Combustion Research Facility (CRF) to allow oxy-combustion and CO_2-recycle operations.
- Design, manufacture, and install an oxy-combustion burner specifically for the CRF.
- Collect data on furnace temperatures, unburned carbon (UBC), gas composition, and flow rates into and out of the furnace.
- Evaluate the effect of various parameters, including firing configuration, oxygen (O_2) purity, CO_2 recycle rate, O_2 concentration, and coal type.

Technical Content

SRI is developing flue gas recycle for oxy-combustion retrofit application to coal-fired utility boilers in order to avoid the excessive flame temperatures that are associated with oxy-combustion and to maintain flow and heat-transfer requirements in the furnace and convective sections.

SRI is conducting the pilot-scale, oxy-combustion experiments using a modified CRF. Figure 1 contains a diagram that represents the CRF with the necessary modifications. These modifications include the addition of an O_2 storage tank and concrete pad; O_2 skid, control, and safety systems; a new burner by Maxon that is designed for O_2 combustion and CO_2 recycle; the additional ducting to allow flue gas recirculation to the burner; and the decrease in ducting size to account for smaller flue gas flow rate.

Technology Maturity:

Pilot-scale using actual flue gas, 25 tonnes of CO_2/day

Project Focus:

Evaluation of Gas Recycle for Oxy-Combustion

Participant:

Southern Research Institute

Project Number:

NT42430

NETL Project Manager:

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Principal Investigator:

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Partners:

CORR Systems
Doosan Power Systems
Linde Gas
Maxon Corporation
Reaction Engineering International
Southern Company

Performance Period:

9/27/05 – 9/25/10

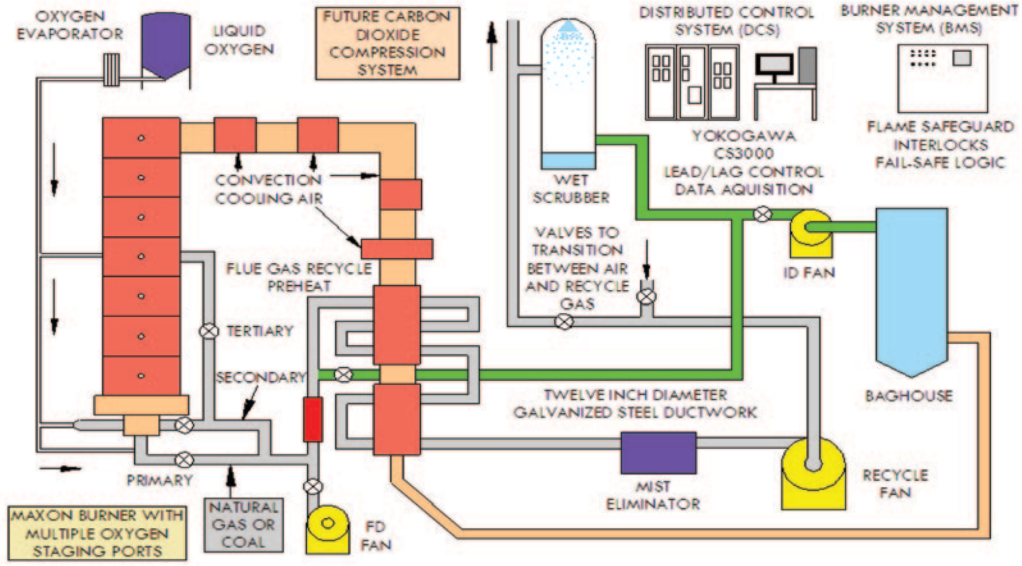

Figure 1: Diagram of the Modified CRF

The CRF is used to investigate the effects of coal type, firing staging, percentage of flue gas recycled, and O_2 purity on oxy-combustion.

In addition to flue gas recirculation, an advanced O_2 burner developed by Maxon is used to allow the flame shape and heat released to be controlled and to provide a stable attached flame. Figure 2 is an image of the flame produced by the oxy-combustion burner.

A preliminary test was performed on the Maxon burner using Illinois Bituminous coal. The test chamber was heated to 2,400 °F with 3% excess O_2. Performance of the burner under air-fired conditions resulted in a nitrogen oxides (NO_x) emission rate of 0.3–0.4 lbs/MMBtu. However, oxy-combustion testing resulted in a lower emission rate of 0.16–0.18 lbs NO_x/MMBtu.

Reaction Engineering International (REI) updated a computational fluid dynamics (CFD) model of the CRF facility to predict oxy-combustion burner performance. The model describes temperatures, reaction rates, char burnout, and NO_x formation and/or destruction as a function of O_2 purity, stoichiometry, coal type, staging, furnace exit O_2 (FEO), and fuel processing. The model was validated by the CRF oxy-combustion experiments and can be utilized for any follow on preliminary designs for project scale up.

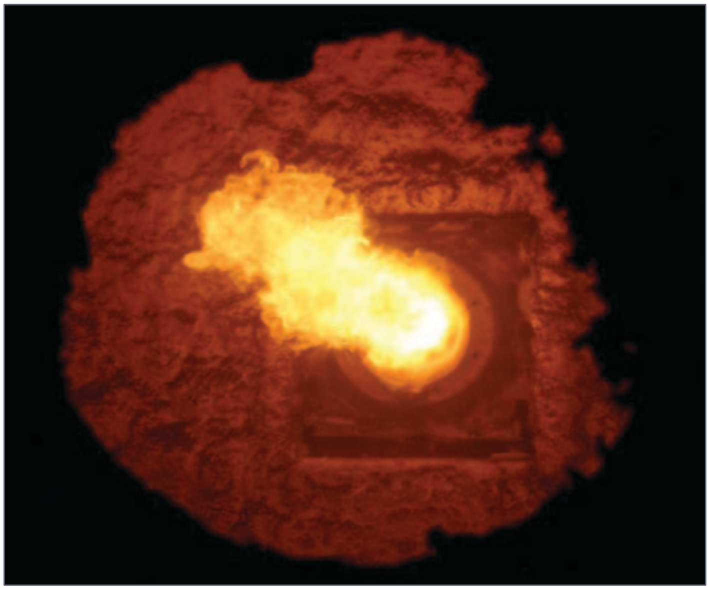

Figure 2: Image of Maxon Oxygen Burner Flame

Technology Advantages

- The oxy-combustion burner is able to maintain a stable attached flame and can light off without natural-gas assist.
- The reduced volume of flue gas produced under oxy-combustion conditions should be less expensive to purify and compress for CO_2 sequestration than flue gas of a conventional air-fired, pulverized coal (PC) plant.

- For plants burning Powder River Basin (PRB) coal, recycling dry flue gas through the coal pulverizers should minimize concern of pulverizer fires.
- Oxy-combustion burners and flue gas recycle rate can be tuned to achieve low-cost operation (i.e., minimize recycle) and maximum heat transfer for a given boiler type and plant configuration.
- Advanced thermodynamic cycles can recover some of the energy penalty associated with air separation for new power plant applications.

R&D Challenges

- Reduce cost of oxy-combustion retrofit for existing plants.
- Reduce energy penalty for O_2 production, which is approximately 25% for conventional cryogenic process.
- Address potential corrosion of low-temperature ductwork and equipment due to flue gas recycle.

Results To Date/Accomplishments

- Completed the oxy-combustion and flue gas recycle retrofit of the CRF.
- Completed the update of the CFD model for oxy-combustion and flue gas recycle.
  - The CFD model was used to predict the flame geometry and temperatures in the CRF and make a comparison with the air-fired case.
  - The CFD model predictions were consistent with the experimental data in showing that the O_2-fired Maxon burner produced lower flame temperatures than the air-fired burner.
- Conducted oxy-combustion and flue gas recycle testing using the CRF.
  - The Maxon staged oxy-combustion burner produced a stable flame over a significant range of firing turn-down, staging, and while firing five different U.S. coal types, including three eastern bituminous coals, a PRB sub-bituminous coal, and a western bituminous coal.
  - The parametric testing included extent of recycle and recycle turndown, FEO percentage, O_2 staging in the burner cup, burner quarl, secondary recycle, and overfire recycle. The load was also varied with and without changes in the amount of recycle flow.
  - The oxy-combustion burner produced lower flame temperatures than for air firing, which should enable safe operation, reduction of recycle flow without concern about furnace flame temperatures, and could be effective at reducing slagging and fouling in the boiler and super heater for full-scale applications.
  - The temperature/time profile was affected by four main factors: (1) the difference in load, (2) the difference in recycle flow back to the furnace and the absence of nitrogen (N_2) flow, (3) the difference in the Maxon oxy-burner design and an air-burner design, and (4) the difference in diffusivity of CO_2 and N_2.
  - Hydrochloric (HCl) acid concentration in the flue gas was consistent with the coal chlorine content and no buildup of HCl was observed via flue gas recirculation.
  - The sulfur dioxide (SO_2) concentration in the flue gas was consistent with the coal sulfur content and no build up was observed via flue gas recirculation.
  - The carbon monoxide (CO) levels were also consistent with that of air firing, and the CO concentration had a significant correlation with only one parameter, that of FEO. Above 1.5% FEO, the CO concentration was around 50 parts per million by volume (ppmv); below 0.5% FEO, the CO concentration could reach hundreds of ppmv.

- The relation of UBC in the ash with FEO was consistent with that of CO. The UBC in the ash increased with increased furnace staging similar to air firing.
- NO_x emissions were high under baseline oxy-combustion conditions. However, NO_x emissions were dramatically reduced with staging of the O_2 in the secondary recycle gas and overfire-recycle flue gas.
- The control system and retrofit concept allowed safe and controlled startup, changing of conditions, continuous operation without buildup of moisture, acid gases, pollutants, or other problems, and yielded efficient combustion of the coal and associated volatile gases.

Next Steps

Project completed September 2010. Final report is under review by NETL.

Available Reports/Technical Papers/Presentations

General project information is available on DOE/NETL website at: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/oxy-combustion/o2firedco2recycle.html

"Oxy-Fired CO_2 Recycle for Application to Direct CO_2 Capture from Coal-Fired Power Plants," 34th International Technical Conference on Coal Utilization and Fuel Systems, Clearwater, FL, June 2009.

"Oxy-Fired CO_2 Recycle for Application to Direct CO_2 Capture from Coal-Fired Power Plants," Annual NETL CO_2 Capture Technology for Existing Plants R&D Meeting, Pittsburgh, PA, March 2009. http://www.netl.doe.gov/publications/proceedings/09/CO2/index.html

MULTI-POLLUTANT CONTROL THROUGH NOVEL APPROACHES TO OXYGEN ENHANCED COMBUSTION

Primary Project Goals

Washington University is developing best practices for implementing oxy-fuel combustion with flue gas recirculation and sorbent processes to minimize nitrogen oxides (NO_x), sulfur oxides (SO_x), particulate matter ($PM_{2.5}$), and mercury (Hg) emissions, and maximize combustion efficiency and the concentration of carbon dioxide (CO_2) in the flue gas through research and experimentation.

Technical Goals

- Measure NO_x emissions resulting from air- and oxy-combustion with CO_2 recirculation.
- Determine the effect of CO_2 recirculation on Hg capture, combustion temperature, flame geometry, etc.
- Experimentally determine the optimum approach to mixing coal, oxygen (O_2), CO_2, and sorbents.
- Determine the effect of the steam temperature to identify the optimum preheating conditions for minimized emissions.
- Develop nano-structured sorbent technologies to reduce Hg emissions.

Technical Content

Oxy-combustion offers several advantages over traditional air-combustion technologies, including higher temperatures and smaller flue gas volume. However, in order to maintain the combustion temperatures at a level that existing, cost-effective materials can handle, the O_2 must be diluted to approximate atmospheric levels. Washington University is researching oxy-combustion that utilizes recirculated flue gas, causing the CO_2 levels in the final flue gas stream to be increased to levels greater than 95%, and controls emissions of NO_x, $PM_{2.5}$, and Hg.

Washington University has also been performing flame types and stability studies for oxy-combustion facilities. The experiments used a 10-25 kW down-fired coal combustor consisting of a non-swirling primary oxidizer (PO) and a swirling secondary oxidizer (SO). The system is run under slight negative pressure and the primary oxidizer preheat temperature was maintained between 300 and 350 °C. Table 1 shows the mole fractions of each component in the PO and SO for all flame studies.

Results from these studies showed that 30 mole percent O_2 is required when using CO_2 as the inert gas to obtain stability results similar to conventional coal air-combustion. Also, inert exchange flames were shown to improve flame stability when compared with conventional coal air-combustion despite the O_2 concentration in the PO being substantially reduced.

Technology Maturity:

Laboratory/pilot scale, 1.2 tonnes CO_2/day

Project Focus:

Multi-Pollutant Control

Participant:

Washington University

Project Number:

NT42531

NETL Project Manager:

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Principal Investigator:

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Partners:

None

Performance Period:

8/29/05 – 2/28/09

Table 1: Flame Types for Oxy-Coal Flame Stability Study

Type		PO Mole Fraction			SO Mole Fraction			T_m* (K)	T_{NB}** (K)
	% O_2 in PO/SO*	O_2	N_2	CO_2	O_2	N_2	CO_2	Fluent Simulation	
A	6% / 35%	6	94	0	35	65	0	2,420	1,860
B	15% / 25%	15	85	0	25	75	0	2,440	1,860
C	21% / 21%	21	79	0	21	79	0	2,480	1,860
D	21% / 25%	21	79	0	25	75	0	2,600	1,930
E	21% / 35%	21	79	0	35	65	0	2,850	1,950
F	25% / 25%	25	75	0	25	75	0	2,720	1,940
G	35% / 21%	35	65	0	21	79	0	—	—
H	35% / 35%	35	65	0	35	65	0	3,010	2,070
I	21% / 35% (N_2/CO_2)	21	79	0	35	0	65	—	—
J	25% / 25% CO_2++	25	23	52	25	0	75	—	—
K	30% / 30% CO_2++	30	21	49	30	0	70	—	—
L	35% / 21% CO_2++	35	23	42	21	0	79	—	—
M	35% / 35% CO_2++	35	25	40	35	0	65	—	—

Notes: Values for component compositions are accurate +/-2%.

1. + Inert balance in both PO and SO is nitrogen (N_2), unless otherwise indicated.
2. ++ Due to eductor, inert balance in PO is not entirely CO_2.
3. * Maximum temperature in temperature profile, as determined from modeling.
4. ** Maximum flame temperature one inch from downstream from burner exit, as determined from modeling.

Technology Advantages

Oxy-combustion offers increased temperature, increased thermal efficiency, reduced pollutant emissions, reduced fuel consumption, and improved flame stability. Oxy-combustion alone, and coupled with unique burner designs, can reduce NO_x emissions beyond levels achieved by using overfire air and low-NO_x burners. Also, oxy-combustion with flue gas recirculation concentrates CO_2 levels, helping to reduce the cost of capture; concentrations up to 95% can be achieved.

R&D Challenges

It was found that the flame structure of non-premixed systems is changed dramatically when oxy-combustion is used.

Results To Date/Accomplishments

- Completed modifications to the oxy-coal combustor to minimize air leakage.
- Developed an understanding of flame geometry under oxy-fuel combustion.
- Developed a simple model that explains the presence of appreciable molecular O_2 at the location of peak temperature in high oxy-fuel combustion.
- Obtained NO_x measurements as a function of stoichiometric mixture fractions for a system that maintained a methane flame at both constant temperature and fuel flow rate.
- Examined the effect of replacing nitrogen (N_2) with CO_2 on the jet exit velocity at start-up for non-premixed jet flames of ethylene.
- The performance of titanium dioxide (TiO_2) with UV irradiation for Hg capture was tested in a bench- and pilot-scale system.

- Flame stability in a Type I laboratory-scale pulverized coal combustor was quantified as a function of inert gas type and O_2 concentration in both the primary and secondary oxidizer streams.
- Developed a model of soot inception limits under oxy-fuel combustion conditions and validated with gaseous fuels.
- Completed a study of blow-off limits in oxy-coal combustion.
- Demonstrated that the approach used to mixing the oxy-coal flame can lead to stronger flames even with reduced O_2 in the primary region.

Next Steps

Project completed February 2009.

Available Reports/Technical Papers/Presentations

Final Report: http://www.osti.gov/bridge/purl.cover.jsp;jsessionid=1D534757947F8B04FBF869761C2461AD?purl=/981333-x4gI1M/

C. E. Baukal, *Oxygen Enhanced Combustion*. CRC Press LLC: Boca Raton, 1998; p 490.

C. J. Sung; C. K. Law, Proc. Combust. Inst. 27 (1) (1998) 1411-1418.

F. Chatel-Pelage; R. Varagani; P. Pranda; N. Perrin; H. Farzan; S. J. Vecci; Y. Lu; S. Chen, Thermal Science 10 (3) (2006) 119-142.

L. Bool; H. Kobayashi; D. Thompson; E. Eddings; R. Okerlund; M. Cremer; D. Wang, 19th Annual International Pittsburgh Coal Conference, Pittsburgh, PA, September (2002).

A MECHANISTIC INVESTIGATION OF NITROGEN EVOLUTION AND CORROSION WITH OXY-COMBUSTION

Primary Project Goals

Brigham Young University (BYU) is investigating the evolution of nitrogen from its origin in coal to emissions in both air- and oxy-combustion. A model of detailed kinetics, devolatilization, and char oxidation in a simple plug flow is also being developed and used to interpret the data.

Technical Goals

- Modify the flat flame burner (FFB) to run using simulated oxy-fuel combustion.
- Modify the multi-fuel flow reactor (MFR) to run with simulated oxy-fuel combustion.
- Gather data through experimental measurements of gas species in air-fired and oxy-fuel pulverized coal flames.
- Develop a computational model of the combustion process, including fuel devolatilization, gas phase kinetic mechanisms, and char oxidation.

Technical Content

The experiments were performed at two facilities designed to investigate the evolution of coal nitrogen species, fuel nitrogen oxide (NO_x) formation, and emissions during combustion processes in air and oxygen (O_2)/carbon dioxide (CO_2) mixtures. A model of detailed kinetics, devolatilization, and char oxidation in a plug flow operation was developed and used to interpret the data collected.

In the experiments performed by BYU, the flue gas was not recycled. Rather, bottled CO_2 was used to simulate dry recycled flue gas. While the results are applicable to entrained-flow pulverized coal combustion in general, the absence of turbulence in the laminar flow experiment is a notable difference from any practical combustor.

Pulverized coal was burned in a refractory-lined, laminar flow reactor referred to as the MFR, shown in Figure 1.

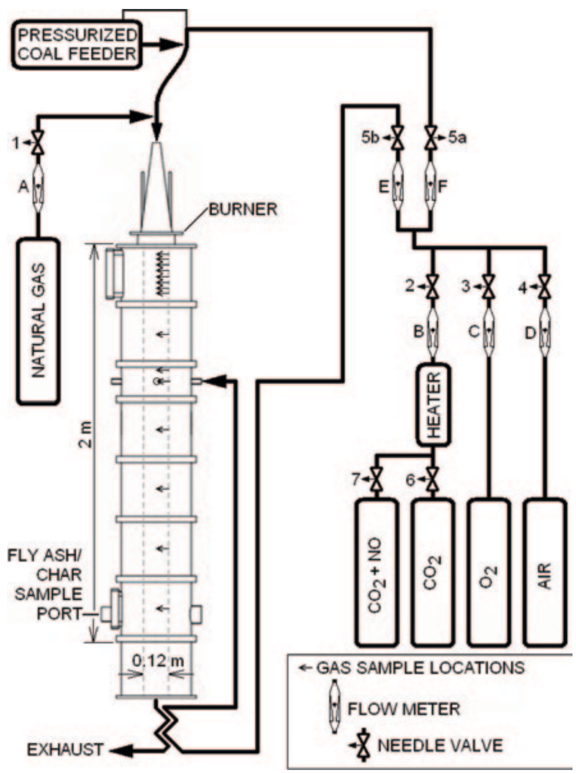

Figure 1: Schematic of the Multi-Fuel Flow Reactor

Technology Maturity:

Pilot-scale using simulated flue gas, 0/05 tonnes CO_2/day

Project Focus:

NO_x Behavior in Oxy-Combustion

Participant:

Brigham Young University

Project Number:

NT42530

NETL Project Manager:

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Principal Investigator:

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Partners:

Air Liquide

Performance Period:

8/4/05 – 12/31/08

The unit at the first facility was a premixed, down-fired staged reactor where the first stage was fuel-rich followed by a burnout oxidizer stage. The oxidizer was varied from air [23% O_2 by mass in nitrogen (N_2)] to two different mixtures of O_2 and CO_2 (25% and 30% O_2 by mass). The coals used were Pittsburgh #8, Illinois #6, and Powder River Basin (PRB). Selected coal properties are shown in Table 1.

Table 1: Selected Properties of the Coals

	Sub-Bituminous	Illinois #6	Pittsburgh #8
Proximate Analysis	DAF wt%	DAF wt%	DAF wt%
Volatile Matter	49.72	44.17	41.96
Fixed Carbon	50.28	55.83	58.04
Ash (wt%, dry)	6.42	9.31	10.67
Higher Heating Value (Btu/lb, DAF)	11,981	14,226	14,785
ASTM Rank	Sub-bituminous A	High-volatile C bituminous	High-volatile A bituminous
Ultimate Analysis	DAF wt%	DAF wt%	DAF wt%
C	70.56	81.88	85.19
H	4.18	4.37	4.87
O	23.63	7.83	4.70
N	1.04	1.27	1.38
S	0.59	4.64	3.86
Total	**100**	**100**	**100**

Both the air and mixture cases produced a rapid initial formation of nitric oxide (NO), with a similar amount of total fuel nitrogen converted to NO. In air combustion, NO can be either formed or reduced by thermal equilibrium forces dependent on the local equivalence ratio. At an initial or primary zone stoichiometric ratio (SR) of 0.82, air combustion appeared to produce thermal NO; while at an SR of 0.65, no evidence of thermal NO is seen. In oxy-combustion, initial NO formation produced concentrations above equilibrium, creating a situation where NO was being destroyed by thermal processes at all measured SR.

There is competition between the NO destruction in the fuel-rich region and the NO formation at tertiary air injection, which creates an effluent out of NO minimum for each oxidizer. The magnitude of the minimum was similar for air- and oxy-fuel combustion; however, the SR at the minimum was higher for oxy-fuel combustion, suggesting that oxy-fuel combustion does not require as deep of a staging environment to achieve NO_x reduction and can therefore achieve higher burnout.

The second facility included an FFB with particle and gas sampling. Char particles were sampled after passing through either air- or oxy-flames. In oxy-flames, the normal diluents of N_2 were replaced with CO_2. The ratio of O_2/CO_2 was varied in order to produce different flame temperatures. There was little difference observed between air- and oxy-fuel pyrolysis of coals.

The probe, shown in Figure 2, was used to sample gas in the reactor.

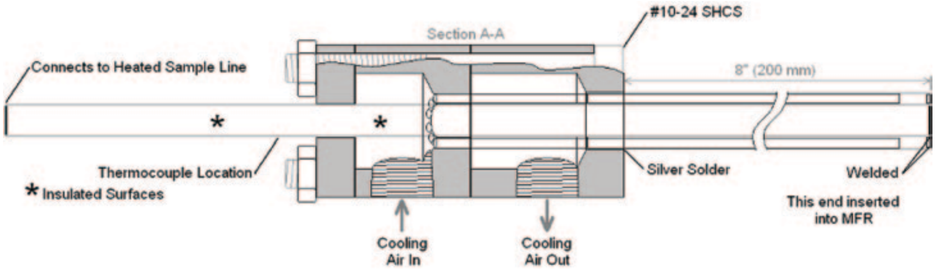

Figure 2: Diagram of the Air-Cooled Gas Sampling Probe

In unstaged, premixed combustion, air- and oxy-fuel combustion produced similar levels of fuel nitrogen conversion to NO_x. Low NO_x emissions from oxy-fuel combustion are therefore not achieved without staged mixing of the oxidizer and fuel as is the case for conventional air combustion.

Technology Advantages

The research will supply information that will significantly aid in the development of oxy-combustion technology.

R&D Challenges

Due to the use of bottled CO_2 to simulate dry recycled flue gas, there was an absence of turbulence in the laminar flow experiment, which creates a notable difference from any practical combustor. This could possibly lead to difficulties when scaling to a commercial plant.

Results To Date/Accomplishments

- Modified the FFB to run using simulated oxy-fuel combustion.
- Modified the MFR to run with simulated oxy-fuel combustion.
- Completed air- and oxy-combustion NO_x profiles with 500 parts per million (ppm) NO added to the reactants to determine the extent of reburning in oxy-combustion.
- Completed a staged combustion experiment of NO_x and major gas species profiles in the MFR.
- Produced a full kinetic mechanism model of oxy-fuel combustion.

Next Steps

Project completed December 2008.

Available Reports/Technical Papers/Presentations

Allam, R. J., R. S. Panesar, V. White, D. Dillon (2005) *Optimising the design of an Oxyfuel-Fired Supercritical PF Boiler*, The 30th International Technical Conference on Coal Utilization and Fuel Systems, April 17–21, 2005, Clearwater, FL.

Andersson, K. (2007) *Combustion Tests and Modeling of the Oxy-fuel Process, An Overview of Research Activities at Chalmers University*, 2nd IEAGHG International Oxy-Combustion Workshop, January 25–26, 2007, Windsor, CT.

Asay, B. W. (1982) *Effects of Coal Type and Moisture Content on Burnout and Nitrogeneous Pollutant Formation*, Ph.D. Dissertation, Brigham Young University, Provo, UT.

Bose, A. C., K. M. Dannecker, J. O. L. Wendt (1988) *Coal Composition Effects on Mechanisms Governing the Destruction of NO and Other Nitrogenous Species during Fuel-Rich Combustion*, Energy and Fuels 2:301–308.

CANMETENERGY CO_2 R&D CONSORTIUM

Primary Project Goals

The CanmetENERGY CO_2 R&D Consortium (Consortium) is conducting oxy-fuel combustion research and development (R&D) using a 0.3 MW_{th} (1 million Btu/h) modular pilot-scale facility. The Consortium has completed nine successive phases of R&D that include oxy-fuel combustion, advanced power cycles, integrated multi-pollutant control, and carbon dioxide (CO_2) capture and compression technologies.

Technical Goals

The technical goal of the Consortium is to develop advanced energy conversion technologies with near-zero emissions for improved efficiency and commercial competitiveness for capture of CO_2 and air pollutants resulting from combustion of fossil fuels. One emphasis of the Consortium research program is the oxy-fuel combustion technology. Since combustion takes place in an oxygen (O_2)-enriched environment, the flue gas comprises mainly CO_2, water, and minor impurities. This CO_2-rich flue gas stream can then be purified, dried, and compressed for pipeline transport and use or permanent storage in geological formations. Oxy-fuel combustion also results in efficiency advances of high flame temperatures and reduced equipment sizes due to lower gas volume.

Technical Content

The Consortium activities in the past have included experimental investigations using coal; coal slurry; bitumen and natural gas to study the characteristics of oxy-fuel combustion; advanced near-zero emissions Brayton and Rankine cycles; solid oxide fuel cell modeling; multi-pollutant capture research for integrated removal of fine particulates, nitrogen oxide (NO_x), sulfur oxide (SO_x), and mercury (Hg); advanced oxy-fuel combustion processes and co-firing with opportunity fuels such as petroleum coke; system components and prototype design and pilot-scale testing; and modeling and development of new CO_2 capture and compression processes.

The latest completed Phase 9 of the Consortium's program included the development of a CO_2 capture and compression unit (CO_2CCU). This unit is capable of separating and compressing CO_2 from combustion flue gas streams for pipeline transport and storage. Part of this work involved the development of a CO_2 high-pressure test cell for studying CO_2 phase change, generating vapor-liquid equilibrium (VLE) data, and studying the impact of impurities in the flue gas stream on the capture processes. This has important practical applications relating to the CO_2 pipeline, material selection, and commercial design of these systems. Other ongoing R&D activities include the modeling of advanced supercritical oxy-coal plants with CO_2 capture; cost analysis; the development and testing of multi-pollutant control strategies, as well as testing in oxy-steam mode; and optimization of a novel multi-function oxy-fuel/steam burner.

Figure 1 shows the major process components comprising the 0.3 MW_{th} oxy-fuel Vertical Combustor Research Facility (VCRF) integrated with the CO_2CCU. The overall pilot-scale research facility is used to develop pollutant control technologies that incorporate a fabric filter or electrostatic precipitator (ESP) for particulate capture, condensing heat exchangers and/or SO_x scrubbing to remove acid gases and oxidized Hg from the flue gas combustion stream.

Technology Maturity:
Pilot-scale research

Project Focus:
Engineering Assessment of Oxy-Combustion

Participant:
CanmetENERGY

Project Number:
IEA-CANMET-CO2

NETL Project Manager:
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Principal Investigator:
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Partners:
Phase 9 Consortium Members: Ontario Power Generation, SaskPower, Governments of Canada and Alberta, Babcock & Wilcox, U.S. Department of Energy, and the CO_2 Capture Project (CCP2)

Performance Period:
9/30/99 – 12/31/09

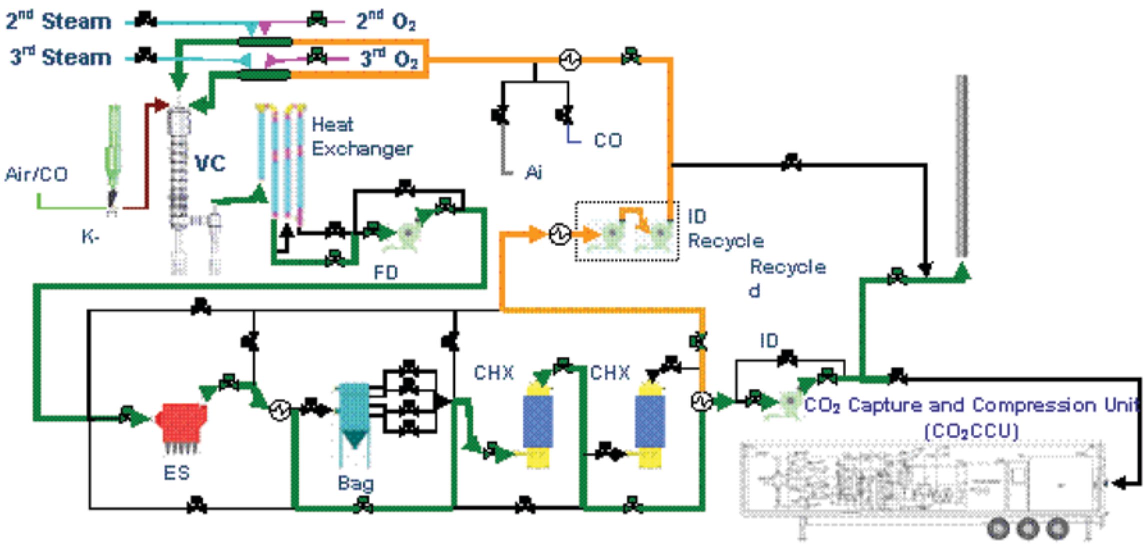

Figure 1: Schematic of the CanmetENERGY's Integrated Oxy-Fuel Vertical Combustor Research Facility

Figure 2 displays the pilot-scale CO_2CCU. The CO_2CCU is capable of processing CO_2 flue gas streams at a maximum rate of 160 Kg/hr with CO_2 concentrations of 50% or higher (in dry volume) to produce a CO_2 product stream with more than 95% purity.

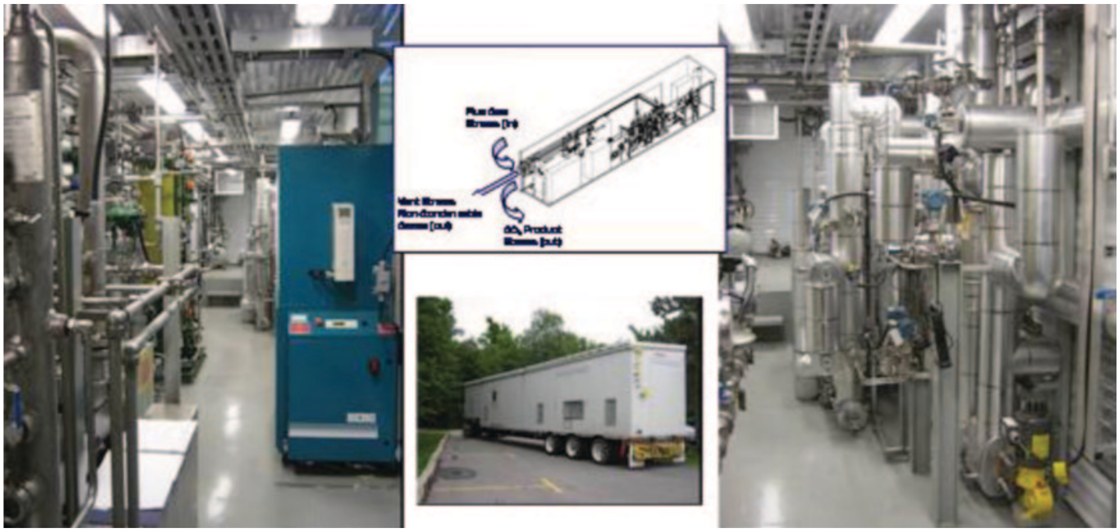

Figure 2: CanmetENERGY's CO_2 Capture and Compression Unit

The high-pressure CO_2 test cell and its high-pressure viewing chamber (HPVC) shown in Figure 3 were used to create super-critical CO_2 and study the CO_2 phase change in a controlled environment. The chamber can handle a maximum pressure of 200 atm and a temperature range of -60 to 150 °C. There are two gas and liquid sample ports located at different heights and optical windows with a camera for observations inside the chamber to study the CO_2 liquid-gas interface.

Figure 3: CanmetENERGY's High-Pressure CO_2 Test Cell and Bench-Scale Facility

Technology Advantages

The program allows research to be carried out at a pilot scale small enough to reduce the overall R&D cost, while the experiments scale is sufficiently large enough to provide proof-of-concept before proceeding to a larger and more costly medium-scale pilot technology demonstration.

R&D Challenges

- Integration and cycle development for O_2/flue gas recirculation (FGR), O_2 combustion, and hydroxy-fuel combustion of fossil fuels in different advanced cycles.
- Improving the understanding of combustion, heat transfer, and emissions in oxy-fuel combustion.
- Development of environmental multi-pollutant controls for NO_x, SO_x, Hg, and particulates.
- Minimizing energy demand for O_2 production while keeping the O_2 purity high.
- Decreasing energy consumption for capture and compression of CO_2.

Results To Date/Accomplishments

- Developed new, ultra-low NO_x oxy-combustion burner and tested the prototype burners in VCRF with sub-bituminous and lignite coals.
- Determined that FE^{3+} salts were capable of oxidizing Hg and achieved a 75% Hg oxidation with an optimal pH between 1 and 3 on bench-scale tests.
- Increased the computational fluid dynamic (CFD) tools for model simulation of oxy-combustion flame characteristics.
- Created a CO_2 capture and compression process simulator and implemented a pilot-scale CO_2 capture research facility that has enhanced the program's CO_2 research capabilities.

- Developed new advanced gas turbine and high-efficiency fuel cell-based power generation cycles.
- Developed models of advanced supercritical oxy-coal plants with CO_2 capture and cost models for economic analysis.
- Developed and tested multi-pollutant control strategies and processes.
- Conducted testing in oxy-steam mode for pulverized coal and performed optimization of a novel multi-function oxy-fuel/steam burner.

Next Steps

DOE/NETL participation in this project ended December 2009. A final report is not available.

Available Reports/Technical Papers/Presentations

General project information is available on DOE/NETL website at: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/oxy-combustion/canmet.html

"Novel Oxy-Steam Burner for Zero-Emission Power Plants," 1st International Oxy-Fuel Combustion Conference, Cottbus, Germany, September 2009.

"Performance of an Advanced Pilot-Scale CO_2 Capture and Compression Unit," 1st International Oxyfuel Combustion Conference, Cottbus, Germany, September 2009.

"An Integrated Approach for Oxy-fuel Combustion with CO_2 Capture and Compression," 7th Annual Conference on CCS – May 5–8, 2008.

EVALUATION OF CO_2 CAPTURE/UTILIZATION/ DISPOSAL OPTIONS

Primary Project Goals

Argonne National Laboratory (ANL) is conducting comparative engineering assessments of carbon dioxide (CO_2) capture retrofit technologies with a focus on oxy-combustion and its possible use as a transitional strategy to integrated gasification combined cycle (IGCC) with carbon capture and storage (CCS).

Technical Goals

- Develop engineering evaluations for oxy-combustion CO_2 capture from existing pulverized coal (PC)-fired power plants retrofitted for flue gas recirculation.
- Identify existing power plants that may be retrofit candidates, considering the effects of coal characteristics and the accessibility of a sequestration site.
- Investigate the potential cost-effectiveness of oxy-combustion retrofits with the All-Modular Industry Growth Assessment (AMIGA) model, regarding least-cost investment and ranking, as well as dispatch order and energy use in the economy.

Technical Content

The project is conducting engineering assessments and economic evaluations on retrofitting PC boilers with oxy-combustion and then eventually repowering the site with IGCC. The engineering assessment for oxy-combustion is being conducted with the ASPEN process model and the economic evaluations with the AMIGA macroeconomic model (see Figure 1). The assessment is investigating the entire life cycle of the plant, which includes the mining of the coal, coal transportation, coal preparation, power generation, environmental controls, water use, pipeline CO_2 conditioning, and pipeline transport of CO_2 for sequestration.

ANL is conducting ASPEN modeling for 18 different oxy-combustion and air-fired cases. Three different power production ratings (150 MW, 300 MW, and 450 MW) are being investigated. The model includes a selective catalytic reduction (SCR) system and a flue gas desulfurization (FGD) system for flue gas clean-up.

ANL is also conducting a net present value (NPV) cost assessment for three alternative scenarios for existing PC plants in order to assess the economic feasibility of retrofitting CCS. The three scenarios are:

1. A base case in which an existing PC plant is operated until retirement in year N and then replaced with an IGCC plant with CCS.
2. An alternative case in which a PC plant with N years of remaining life is replaced in year zero with an IGCC plant with CCS.
3. An alternative case in which a PC plant is retrofit in year zero with oxy-combustion and CCS with subsequent replacement of the plant in year N with IGCC, such that the existing oxygen plant and CO_2 recovery system can be used by the IGCC plant.

Technology Maturity:

Systems analysis and macroeconomic modeling

Project Focus:

Engineering Assessment of Oxy-Combustion

Participant:

Argonne National Laboratory

Project Number:

FWP-49539

NETL Project Manager:

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Principal Investigator:

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Partners:

None

Performance Period:

10/1/97 – 12/31/10

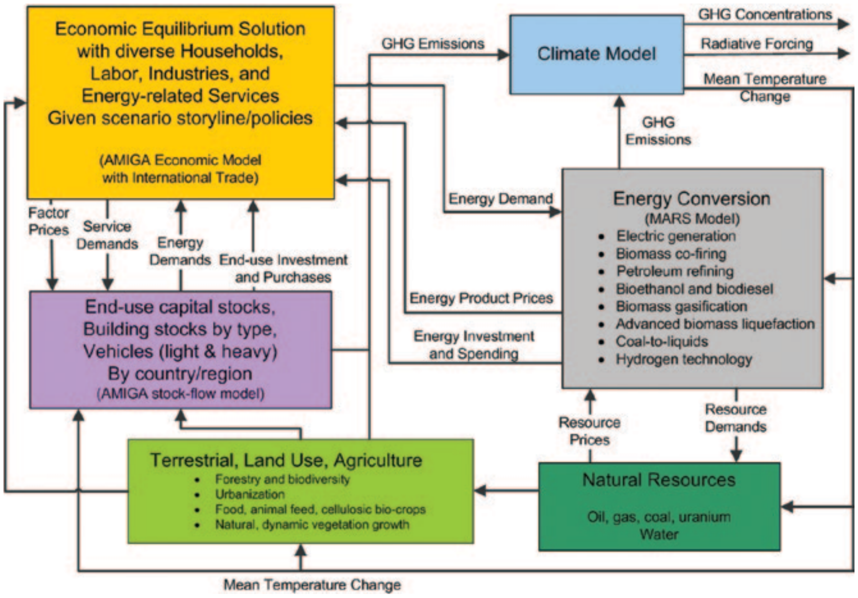

Figure 1: AMIGA Modeling System

Technology Advantages

- Post-combustion CO_2 capture systems that treat conventional flue gas are critically dependent upon deep levels of sulfur dioxide (SO_2) clean-up to protect solvents. Oxy-combustion does not require that level of SO_2 reduction.
- For plants envisioning repowering, there is an advantage to using oxy-combustion because the air separation unit (ASU) system can be transitioned to the new repowered system.

R&D Challenges

Lowering the cost of oxygen production and clean-up.

Results To Date/Accomplishments

- There is an Oxyfuel Power Plant Base Case operating using ASPEN 23.0 with the refinement of system pressure drop calculations and the incorporation of a hierarchy block for the FGD system reflecting the performance criteria as calculated in the separate detailed ASPEN 23.0 model with aqueous electrolytes.
- An ASPEN 20.0 model for the full steam cycle is available.
- In order to better understand the link between compression energy and oxygen impurity compositions, an ASPEN 23.0 model for the ASU was developed and compared against current system performance.
- An ASPEN 23.0 FGD model using Electrolyte Wizard was developed to address retrofit details.
- An ASPEN 23.0 model of the CO_2 conditioning section was developed so that a 50 parts per million (ppm) oxygen (O_2) specification of the pipeline product is met.
- A full energy-cycle was evaluated based on simulation of an oxy-combustion, PC boiler with flue gas recirculation, and CO_2 capture.
- Process design and economics for 300- to 900-MW PC-fired boilers with low-, medium-, and high-sulfur coals indicate that the oxy-combustion strategy is economic and could be an approach to lower the costs of eventually repowering a site with an IGCC system.

- AMIGA was compared to the Second Generation Model (SGM), which is a competing climate economical model from the U.S. Environmental Protection Agency (EPA).
- AMIGA projects a ramping-up of oxy-combustion retrofits with deployment peaking in 2035.
- AMIGA projects a different investment strategy than some competing macroeconomic models.

Next Steps

Project completed December 2010. Final report under development.

Available Reports/Technical Papers/Presentations

General project information is available on DOE/NETL website at: http://www.netl.doe.gov/technologies/coalpower/ewr/co2/oxy-combustion/evaluation.html

“Evaluation of CO_2 Capture/Utilization/Disposal Options,” NETL Fact Sheet.

“ANNUAL REPORT 2009: Evaluation of CO_2 Capture and Sequestration Using Oxyfuels with AMIGA Economic Modeling,” November 23, 2009.

“Economics of CCS Systems – Potential Investment into CCS Technologies Stimulated by a ‘Carbon’ Market,” 8th Annual Conference on Carbon Capture and Sequestration, Pittsburgh, PA, May 4–7, 2009.

“Representing technology in CGE models: a comparison of SGM and AMIGA for electricity sector CO_2 mitigation,” Int. J. Energy Technology and Policy, 6:4 (2008) p.323.

“CO_2 capture and sequestration: Technology options for new and retrofit applications,” 2nd U.S. – China CO_2 Emissions Control Science and Technology Symposium, Zhejiang University Hangzhou, People’s Republic of China, May 29–30, 2008.

“High-sulfur Coal Desulfurization for Oxyfuels,” 7th Annual Conference on Carbon Capture and Sequestration, Pittsburgh, PA, May 5–8, 2008.