JUPITER OXYGEN Combustion technology of Coal and other Fossil Fuels in boilers and furnaces

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ABSTRACT

Jupiter Oxygen Corporation has developed combustion technology systems using one hundred percent oxygen for coal and other fossil fuels with dramatic benefits. It virtually eliminates combustion air created NOx since ambient air is excluded, and is expected to reduce coal combustion NO_x levels below 0.10 Lbs/MMBtu fuel input with properly designed combustion and burner systems. Also, it significantly reduces other greenhouse gases, except for CO_2 which is highly concentrated in the flue gas making capture easy. Furthermore, it significantly reduces the amount of fossil fuel needed to create energy.

Significant progress has been made in experimental investigations of oxy-fuel combustion for $C0_2$ capture purposes at the Jupiter Aluminum Combustor Research Facility.

Detailed burner flame measurements have revealed insights on development and pollutant formation characteristics over a wide range of operating conditions using natural gas and coal. This study marks the first use by Jupiter Oxygen Corporation to develop and design 100% Oxygen based combustion systems. Its focus is on evaluating combustion and burner system design concepts for 100% oxygen and coal combustion with and without recycled flue gas. Test results indicate that a new combustion and burner system design approach can potentially reduce NOx at boiler or furnace exit below 0.10 Lbs/MMBtu Coal input and below 0.05 Lbs/MMBtu for Natural Gas input.

INTRODUCTION

In the 1990s, Dietrich Gross, Chairman and CEO of an industrial company, was concerned about the rising cost of fossil fuel and environmental issues for his business. He envisioned the use of oxygen instead of air for natural gas aluminum melting furnaces. This led to experiments with the use of oxygen in industrial melting furnaces. Knowledge from these experiments led to a new technology for combustion and burner systems for the oxy-fuel combustion process running very close to stoichiometric conditions without ambient air. Although flame temperature exceeded 4,500 degrees °F, and reached as high as 5,300 degree °F, industrial melting furnace process temperatures were maintained at the same levels as with conventional types of combustion without damage. The molten metal process temperature remained about 1,400 degrees °F, with wall temperatures about 1,800 degrees F, and stack temperature about 1,000 degrees °F.

The results of using this new technology in industrial melting furnaces were quite dramatic. Compared to traditional air-fossil fuel, equivalent product was produced with a natural gas fuel reduction of up to 73% and a waste oil fuel usage reduction up to 68%. For aluminum, 1,008 Btu/Lb was the average energy requirement, which improved to 750-900 btu/lb with continuous runs eliminating holding time. This compares to the prior experience with air fuel of about 3,620 Btu/Lb, which was expected for air fuel combustion in that industry segment.

The oxy-fuel technology transfer then was made from industrial melting furnaces to fossil fuel steam generators and power plants, focusing on efficiency and emissions benefits. Cooperation was received from the Vice-President's Energy Task Force, the Department of Energy, and its National Energy Technology Laboratory.

In addition, the capture and sequestration of $C0_2$ emissions from fossil fuel power plants and melting furnaces can be achieved via oxy-fuel combustion, which reduces or completely eliminates nitrogen from the feed gas to the combustor and hence produces a flue gas with high $C0_2$ concentration. A goal is to develop viable and optimal techniques for the design or retrofit of fossil fuel power plants and melting furnaces in order to recover $C0_2$ for utilization in enhanced oil recovery or coal bed methane projects as well as other industrial applications.

Description of the JUPITER Boiler Combustor Research Facility

This pilot-scale test facility is dedicated to Natural Gas and Coal Oxy-Burner combustion and burner systems development and testing as well as $C0_2$ capture studies. Also, the test results provide valuable insights on the impact on combustion performance due to combustion medium, burner swirl and burner configuration.

The test boiler is a Keeler 'D'-type saturated steam boiler designed to be fired with a single air-fuel natural gas burner. The boiler is rated at 12,500 lb/hr and 250 psig.

Modifications to the Keeler Boiler for Oxy-Gas operation.

The air-fuel burner has been replaced by 4 Maxon designed Oxy-GAS burners each rated for approximately 4 MMBtu/hr. The burners were equally spaced in the firebox in a 2 x 2 array.

Oxygen flow to the burners was controlled by a flow control rack that allows the oxygen rate to be adjusted for each of the 4 burners. The oxygen flow rate was pre-determined by calculation but could be adjusted while online to optimize operation.

Each of the four burners had individual oxygen flow meters for independent control and monitoring. Natural gas flow was measured by a temperature and pressure compensated orifice plate type smart transmitter.

The boiler set up was equipped with the instrumentation described below.

The feedwater flow meter is a magnetic flow tube and transmitter that is not temperature or pressure compensated. Compensation was done manually in the boiler performance calculations.

The steam flow meter is an orifice plate type connected to a smart transmitter which calculated flow based on the pressure loss across the orifice and compensated for both line pressure and temperature. Steam temperature is monitored with an RTD mounted upstream of the orifice plate.

Steam quality was measured using an Ellison-Type Calorimeter located downstream of the steam drum and upstream of the steam flow meter. The appropriate size orifice plug was installed to ensure isokinetic sampling of the steam and the flow calculated so that it could be added to the total quantity of steam generated.

The exiting steam was cooled by water injection in the steam line before condensing into the feedwater tank.

Flue gas from the boiler exits through 6" diameter stack for Natural Gas testing and a modified 8" diameter stack for Coal Testing to allow for accurate velocity measurements to calculate flue gas rates.

Gas sampling for NO_x, SO_2 and CO emissions were measured in the stack sampling ports located inside the building. Particulate emissions testing (including metals analysis) and flow rates were measured in the 8 inch stack located outside the building on the roof.

PERFORMANCE TEST RESULTS

Natural Gas and Air (Base Line Data)

Performance data for original Boiler configuration firing Natural Gas with Air
* Based on Products of Combustion and Estimated Casing Heat Loss of 1.2%

Test Config Original Gas/Air	**Boiler Efficiency (%) Based on Steam/Fuel**	**Boiler Efficiency (%) Based on Flue Gas**	**Average Boiler Efficiency (%)**	**NOx Emission ppm (lb/MMBTU)**	**CO Emission ppm (lb/MMBTU)**
Average of 2 test over 4 Hrs	***76.25***	***75.45***	***75.85***	***60 (0.092)***	***187 (0.189)***

PERFORMANCE TEST RESULTS Natural Gas and Oxygen

The tests were done for two operating conditions:
1) Low CO / High Combustion Efficiency (higher NO_x)
2) High CO / Low NO_x
3) The following results are from first generation burners and combustion systems and are expected to improve with additional development.
4) The reason for the high and low CO operation was to study the effects of different O_2 levels

Test Config	**Boiler Efficiency (%) Based on Steam / Fuel**	**Boiler Efficiency (%) Based on Flue Gas ***	**Average Boiler Efficiency (%)**	**NO_x Emission ppm (lb/MMBTU)**	**CO Emission ppm (lb/MMBTU)**
Low CO Run 1 Nov 15/02 14:02-14:32	***85.6***	***87.6***	***86.6***	***435 (0.056)***	***144 (0.011)***
Low CO Run 2	***86.0***	***87.4***	***86.7***	***450***	***120***

Nov 15/02 14:33-15:04				***(0.058)***	***(0.009)***
High CO Run 1 Nov 15/02 15:14-15:44	***85.2***	***87.7***	***86.5***	***335 (0.041)***	***15042 (1.112)***
High CO Run 2 Nov 15/02 15:44-16:14	***85.5***	***87.6***	***86.6***	***337 (0.042)***	***13651 (1.024)***
Low CO Run 1 Nov 18/02 09:21-10:21	***85.0***	***87.6***	***86.3***	***481 (0.065)***	***18.8 (0.002)***
High CO Run1 Nov 18/02 16:00-16:30	***84.4***	***87.8***	***86.5***	***362 (0.045)***	***16434 (1.245)***

The above data compared to the Original performance data shows an efficiency improvement of 10.85 % and NO_x improvement of .051 to .035 lb/MMBTU

SUMMARY OF OXY-FUEL BOILER PERFORMANCE TEST RESULTS Using oxygen-natural gas burners

1. Using oxygen-natural gas burners in the boiler resulted in steady state operation at approximately 75% of the rated boiler capacity.

2. Maximum tube temperatures and target wall temperatures were maintained below 2300 deg. F and there appeared to be no fireside damage to the boiler tubes or refractory walls.

3. When operating the burners in a high CO mode, the NO_x emissions ranged between 0.041 to 0.045 lb/MMBTU.

4. When operating the burners at normally accepted CO emission levels, the NO_x emissions ranged between 0.056 to 0.065 lb/MMBTU. However, based on laboratory results, these values are expected to be in the .03 to .04 range with further medications and improvements.

5. There appears to be no significant difference in boiler efficiency whether the burners are operated at high or low CO emission rates. The boiler efficiency ranged from 86.1% to 86.7% based on an average of the efficiencies calculated using the measured steam rates and products of combustion.

6. Test results and boiler /burner operation were repeatable at various test conditions.

7. These tests were conducted at relatively low ambient air temperatures. It is estimated that the boiler efficiency would be 0.5% higher if the ambient temperatures were more typical of a standard boiler house where temperatures would be 40 to 50 degrees higher than these test conditions.

Oxy-Coal Burner Set Up

Modifications to the Keeler Boiler for Oxy-Coal operation

The major objectives of this series of test were

To determine if there would be damage to the boiler tubes or refractory resulting from the heat from the combustion of Coal with 100% Oxygen.

To determine the effectiveness, volumes and velocities of CO_2 required to transport the coal from the feeder to the burners. The CO_2 was required to simulate partial flue gas recirculation for the transportation of the coal to the burners. No other flue gas recirculation was required for this type of boiler.

Determine the performance of the Oxy-Coal Burners.

Determine flame stability of the Oxy-Coal Burners.

Modifications

The air-fuel burner has been replaced by 4 Maxon designed Oxy-Coal burners each rated for approximately 2 MMBtu/hr. The burners were equally spaced in the firebox in a 2 x 2 array. A fifth oxy-natural gas burner was installed in the center of the coal burner array to be used to preheat the boiler prior to firing with coal. During the coal tests, the center gas fired burner was not operational.

The coal feed system consisted of two coal hoppers equipped with rotary pocket feeders and a precision screw feeder to meter the amount of coal entering the burners. Each hopper supplied coal to 2 burners each (one for the upper burners and one for the lower burners). The feed system was designed to transport approximately 200 lbs/hr to each of the 4 burners (total 800 lbs/hr). Each coal hopper had a 1000 lb. capacity to allow for 2.5 hours of run time.

The coal from the screw feed dropped into a venturi eductor that was open to atmosphere. Each eductor was supplied with 130 scfm of carbon dioxide to be used as the coal transport media. The CO_2 was a tank equipped with a steam heated vaporizer capable of supplying up to 400 cfm of CO_2. The CO_2 rates were monitored using orifice plates and flow transmitters connected to the Maxon control panel.

The coal feed pipes were designed to minimize flow imbalances to the burners by using symmetrical and parallel routing for both the upper and lower burner sets. Long radius bends were used to minimize stratification and pressure imbalances for uniform coal flow to each of the 4 burners.

The boiler set up was identical to the previous OXY-GAS testing, equipped with the instrumentation. However, the boiler was equipped with 2 explosion vents and an air-cooled camera system installed in a sight port located on the opposite wall of the burners. The camera allowed constant monitoring of the burner front in case of a flame-out. It was also used as a diagnostic tool for assessing the flame shape and quality.

At the end of the test, the amount of coal remaining in the hoppers was weighed to calculate the average coal feed rate over the test.

The same boiler test was repeated (as described above) on a successive day to ensure repeatability of boiler / burner operation and performance.

TEST COAL PROPERTIES

As Fired

% Moisture	% Ash	% Volatile	% Fixed Carbon	BTU/lb	% Sulfur
16.12	***1.06***	***42.59***	***40.23***	***10372***	***0.09***

Ultimate Analysis

Constituent	% Dry Basis
Ash	**1.26**
Hydrogen	**5.19**
Carbon	**73.66**
Nitrogen	**0.98**
Sulfur	**0.11**
Oxygen	**18.80**

PRELIMINARY PERFORMANCE TEST RESULTS

The following results were determined from the boiler performance tests conducted on January 9 and 10, 2003.

Coal Feed Rate Determination from the Boiler Performance Test

Start Weight (lb)	Finish Weight (lb)	Coal Used (lb)	Time (min)	Average Feed Rate (lb/min)	4 Burner Feed Rate (lb/hr)
780	***236***	***544***	***101***	***5.39***	***646.8***

The above rate (646.8 lb/hr) was used in the performance calculations.

The following performance test results were measured on two successive days. The efficiency was lower and NO_x levels were higher as a result of the large amounts of air in-leakage through the venturi eductor that was open to atmosphere.

Test Config	NOx Emission ppm (lb/MMBTU)	CO Emission ppm (lb/MMBTU)
Run 1 Jan 9/03 16:00-17:00	***1250 (0.635)***	***5.28 (0.002)***
Run 2 Jan 10/03 19:45-20:45	***1223 (0.639)***	***1.49 (0.0005)***

DISCUSSION of OXY- COAL BOILER PERFORMANCE TEST RESULTS

Using oxygen-coal burners, the boiler was operated at approximately 42% of the rated boiler capacity. The original intention was to operate at approximately 50% to 52% of the rated capacity based on a total coal feed rate of 800 lbs/hr and a coal HHV of 10372 BTU/lb (as fired). However, the coal feed system did not deliver the design coal flow rates and was found to be operating at an average of 646 lbs/hr.

Based on the most recent coal analysis and the data collected during the testing, the average overall boiler efficiency was calculated to be 82.4% prior to any adjustments, which are discussed below.

The efficiency of the boiler was calculated to be 82.4% based on the energy absorbed by the steam compared to the total energy available in the coal. The energy available in the coal was determined using a calorimeter and is the maximum possible assuming both the reactants and products are at the standard temperature and the water in the products condenses.

A number of factors in this test detracted from the efficiency of the boiler. For example, since the test was conducted in an unheated area, 1.03% of the total energy released by the coal was required to heat the ingressive air from the ambient temperature (27 ºF) to the temperature of the product gases (355 ºF). Likewise because of cold testing conditions, 0.36% of the total energy released by the coal was required to heat the coal and oxygen from the ambient temperature to a value that is standard for calorimeter tests (77 ºF). The efficiency of the boiler could be improved another 1.24% if the exhaust gases were used to preheat the CO_2 carrier gas to 250 ºF. Finally, energy lost to the environment but not directly measured accounted for 6.6% of the total energy released by the coal. Typically, heat transfer from the boiler to the ambient amounts to 1.2% of the energy, leaving a difference of 4.4% [6.6%-1.2%] unaccounted energy loss. The addition of all accounted and unaccounted losses represents 7.03% of the total energy released by the coal.

The ingressive air has at least three additional factors that detract from the overall performance of the boiler, further reducing efficiency. As discussed earlier, the air absorbs energy from the flame with no useful output. Second, the air reduced the flame temperature, which reduces the effectiveness of the radiant heat transfer. Third, the increase flow rate through the boiler reduces the gas residence time, which also reduces the heat transfer. While these effects cannot be quantified with the test data, it is understood qualitatively that they reduce the overall efficiency of the boiler, as well as inefficiencies due to operating the test at a 42% load. Significantly improved efficiency is expected with further development based on the industrial furnace and natural gas-oxygen results.

Lab scale results have shown NO_x of 0.10 lb/MMBTU or less. The reason for the excessive NO_x emissions is due to the large amount of air infiltrating the coal feeder system. The original intention was to have only CO_2 as the coal carrier gas, therefore minimizing nitrogen quantities and NO_x. However, since the eductor induced draft at the coal insertion interface was high, a large amount of air was pulled into the carrier stream. It has been calculated that the air quantity was approximately 178 scfm (for both educators). The total amount of coal carrier gas (CO_2) was 260 scfm, therefore the air quantity was almost 70% of the CO_2 quantity. The 4 major effects of the air infiltration are as follows:

1. Nitrogen from the ambient air causes more thermal NO_x to be generated.

2. Oxygen from the air changes the combustion zone stoichiometry.
With higher amounts of oxygen available at the combustion zone, more fuel NO_x could be generated.

3. The coal pipe velocities would be much higher causing the coal discharge momentum to be much higher and create combustion zone problems that were not anticipated in the design. This could cause higher NO_x and LOI (unburned fuel).

4. The amount of air pulled into the system needs to be heated and therefore boiler efficiency will be reduced due to higher losses based on the quantities of combustion products (particularly nitrogen which is not used in combustion)

Therefore, with the air entering the system eliminated, it is expected that the NO_x emissions would be greatly reduced and that the efficiency would be significantly increased..

It should also be noted that the coal used in this test has a low higher heating value (10372 BTU/lb) with relatively high amounts of moisture and oxygen. Depending on the type of coal used, the NO_x emissions could be reduced using a coal with lower nitrogen content and higher heating value. Normally NO_x emission limits are associated with a particular type of coal being used. .

Maximum tube temperatures and target wall temperatures were maintained below 2300 deg. F and there appeared to be no fireside damage to the boiler tubes or refractory walls at the 42% boiler load used during these tests.

Review of the major objectives of this series of tests:

To determine if there would be damage to the boiler tubes or refractory resulting from the heat from the combustion of Coal with 100% Oxygen.

Results: Both with Natural Gas and Coal there was no signs of refractory damage or water wall tubes. Prof. Douglas Stamps was asked to evaluate this area of the testing program. The following is a summation of his findings.

Discussion and explanation of why the boiler tubes did not overheat

A notable feature of the fuel-oxygen tests is that the boiler tubes did not degrade despite significant increases in the flame temperature. For example, a flame temperature of 5030 F was calculated for a natural gas-oxygen mixture as compared to a value of 3540 F for a natural gas-air mixture. In order to understand why the boiler tubes did not melt with such high temperatures within the boiler, a simplified model was developed to predict the boiler tube temperatures.

An idealized model was developed of the boiler to understand the dominant physics of the heat transfer from the gas to the boiler tubes and subsequently to the two-phase water inside the tubes. The model was constructed as the sum of the radiation and convective heat transfers into the boiler tubes balanced by the heat removed by the conduction through the tube and the boiling of the water within the tube.

The heat transfer within the boiler is complex. Radiation and convective heat transfers dominate within the boiler. The heat transfer within the boiler is complicated by the geometry, which allows a surface to radiate to many other surfaces at different temperatures as well as to the gas whose temperature varies spatially throughout the boiler. The idealized model was constructed of two plates separated by the combustion products. One plate was the refractory material and the other was the tube surface. A two-temperature model of the gas was employed. The gas next to the refractory plate was assigned the flame temperature. The gas next to the tube surface was assigned a temperature equal to the average temperature of the gas, which was defined as the average of the flame temperature and a typical temperature of the flue gas. Representative values were used for material properties and heat transfer coefficients. The gas was assumed to be both absorbing and transmitting of radiation. Its radiative characteristics were characterized by both temperature and composition dependent emittance values that were corrected for the combined effects of both carbon dioxide and steam. The model resulted in coupled equations for the radiosities of the refractory and tube plates that were solved iteratively using assumed values of the tube temperature until the radiative and convective heat transfers to the tubes equaled the heat transfer through the tubes.

The results showed that the tube temperature for a natural gas-oxygen fired boiler was higher than that of a natural gas-air fired boiler but not enough to damage the tubes. For example, the outer surface of the tube was predicted to be 1520 F for the fuel-oxygen case when the gas inside the boiler was at 5030 F near the refractory plate and 2690 F next to the tubes. This compares to an outer tube temperature of 980 F for the fuel-air case when the gas inside the boiler was at 3540 F near the refractory plate and 2030 F next to the tubes. The temperature of the two-phase water was 340 F for both cases. Both cases used the same values for parameters except for the gas emittances and the convective heat transfer coefficient.

The main contributor to keeping the tubes from melting is the effective overall heat transfer coefficient associated with the flow of the boiling water. Gas side convection plays a role in moderating tube temperatures although this effect is sensitive to the local gas temperature and flow rate of the gases.

To determine the effectiveness, volumes and velocities of CO_2 required to transport the coal from the feeder to the burners.

The CO_2 was required to simulate partial flu gas recirculation for the transportation of the coal to the burners. No other flu gas recirculation was required for this type of boiler.

Determine the performance of the Oxy-Coal Burners.

The burners for first generation design performed quite well. The flame shape was long and somewhat narrow. Future generation burners will have a shorter wider flame.

The NO_x Levels were high as a result of the air entrainment through the coal feeder and this added gas contributed to the long flame. Elimination of this problem should shorten the flame and considerably reduce the NO_x Levels.

Determine flame stability of the Oxy-Coal Burners.

The air-fuel burner has been replaced by 4 Maxon designed Oxy-Coal burners each rated for approximately 2 MMBtu/hr. The burners were equally spaced in the firebox in a 2 x 2 array. A fifth oxy-natural gas burner was installed in the center of the coal burner array to be used for start up and was turned off when the first coal burners were brought on line. Overall stability of the flame was excellent.

The Patent

During this time period, Mr. Gross applied for and received a United States patent for the new oxy-fuel combustion technology, and has parallel patent applications pending in much of the world. In addition, Mr. Gross has certain related patent applications pending. The patent rights have been assigned to a new energy technology company, Jupiter Oxygen Corporation in Schiller Park, Illinois, U.S.A. For further information, contact the company's vice-presidents, Mark Schoenfield [m schoenfield@jupiteroxygen.com] or Alex Gross [a gross@jupiteroxygen.com].

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