Oxy-fuel Combustion Systems for Pollution Free Coal Fired Power Generation

Tom Ochs[‡]
Danylo Oryshchyn[‡]
Dietrich Gross[†]
Brian Patrick[†]
Alex Gross[†]
Cindy Dogan[‡]
Cathy Summers[‡]
William Simmons *
Mark Schoenfield[†]

[†]Jupiter Oxygen Corporation
[‡]USDOE/Albany Research Center
* CoalTeck LLC

e-mail: m_schoenfield@jupiteroxygen.com

ABSTRACT

Jupiter Oxygen's patented oxy-fuel combustion systems[1] are capable of economically generating power from coal with ultra-low emissions and increased boiler efficiency. Jupiter's system uses pure oxygen as the combustion agent, excluding air and thus nitrogen, concentrating CO_2 and pollutants for efficient capture with near zero NO_x production, reducing exhaust mass flow, and increasing radiant heat transfer. Flue-gas recirculation rates can be varied to add flexibility to new boiler designs using this technology. Computer modeling and thermal analysis have identified important design considerations in retrofit applications.

INTRODUCTION

Oxy-fuel combustion and flue gas recirculation systems have shown substantial promise for reducing pollutants and greenhouse gases in existing fossil fuelled electric power generation plants. They provide an innovative path to increase the use of secure domestic fuel supplies, while concurrently reducing our dependency on foreign fuel sources, and greatly reducing the negative environmental impact with which coal has been long associated. As a commercially proven technology in manufacturing, it is now emerging as one of the most promising technologies for use in coal fired power plants. The clean, efficient combustion process not only facilitates the use of our abundant coal supplies in an environmentally responsible way, but also provides both improved national security and a stable energy supply to support economic growth. It is likely that no single solution will be found for our Nation's energy supply problems; however, it is advanced

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concepts such as oxy-fuel combustion that can give the energy sector a selection of solutions for environmentally sound energy production.

With this in mind, Jupiter Oxygen, in cooperation with the DOE Albany Research Center (ARC), embarked on a project to develop computer models which indicate that the use of flue gas recirculation with oxygen supported combustion (resulting in the virtual elimination of nitrogen) can be effectively put into operation on existing power plants. Computer modeling will be supplemented by experimentation to verify and improve the models. Additionally, though earlier studies have thoroughly investigated the economics of oxy-fuel to ensure commercial feasibility, this paper has identified some other areas advantageous to the use of oxy-fuel systems.

In a power generation system, it is important to take into consideration both the steam being generated and the equipment that is using that steam. Power plants operate at design steam temperatures and pressures and significant deviations from those design conditions can damage the equipment in the steam loop such as turbines and feedwater heaters. Modeling combustion under high-oxygen conditions indicates that increased flame temperatures will result, with a concurrent increase in radiant heat transfer in the boiler. Since the oxygen content of the gas supporting combustion has a direct effect on the flame temperature, it presents opportunities to 'tune' the flame temperature for the particular boiler system involved by varying the amount of recycled flue gas to regulate heat transfer. The significantly different heat transfer properties of flue gas, which comprises carbon dioxide, water vapor, and oxygen rather than air which is composed predominantly of nitrogen and oxygen are taken into account. The specific impact of such a system on thermal efficiency and power output is sensitive to the arrangement and relative size of heat transfer surfaces in the particular power plant being modeled (described below). The net result of the modeling has shown that while maintaining a constant O_2 flow rate, the flow rate of recirculated flue gas can be varied to change the heat transfer conditions, such that power plant performance can be optimized using recycled flue gas while making certain that the design conditions are met, ensuring the safe and long-term operability of the boiler.

Finally, the use of oxy-fuel systems results in a post-combustion gas stream that may be processed to more easily remove all pollutants (particularly sulfur oxides, mercury, and particulates – i.e. PM 2.5) and CO_2. Combined with the known dramatic reductions in NOx, virtually emission-free power production is the ultimate result.

Modeling

In oxy-fuel combustion as patented by Jupiter Oxygen Corp. and modeled at the USDOE/ARC, air is not used to support the firing of fuel in the boiler. Instead, oxygen, augmented with recirculated flue gases from the boiler exhaust, is used to fire the fuel in the boiler. The composition of the incoming combustion gas and outgoing exhaust are markedly different from those found in air-supported combustion. One benefit of this difference in composition is the amenability of oxy-fuel exhaust to flue-gas cleaning methods, especially those which seek to remove CO_2, mercury, and PM 2.5 from the gas stream released to the atmosphere from the boiler. The team at the USDOE/ARC is also modeling a flue gas cleaning process which uses oxy-fuel exhaust as input.

Modeling the retrofit of existing power plants for oxy-fuel combustion highlighted the following considerations:

- Thermal efficiency and capacity of existing power plants modified to use oxy-fuel combustion technology
- Amount of steam produced in the radiant zone of a boiler firing with oxygen in concentrations higher than the oxygen content of air
- Temperature to which the oxy-fueled boiler can superheat the steam
- Materials limitations under higher-temperature oxy-fuel conditions
- Changes in the composition of flue gas
- Alternative methods to power the cryogenic plant
- Resultant emissions using Integrated Pollutant Removal

GE GateCycle® software[°] was used to model the characteristics of power generation in an oxy-fuel system. The basic models include a simulated subcritical single reheat PC unit (2,400 psi (16.55 MPa), 1,004°F (540°C), 1,004°F) and a mildly supercritical double reheat PC unit (3,500 psi (24.13MPa), 1,050°F (566°C), 1,050°F, 1,050°F). The model units are designed to a 400 MW capacity and use “wet flue gas recirculation.” In wet recirculation, moisture is retained in the recirculated portion of the flue gas and the temperatures throughout the recirculation system are kept above the dew point. In the models, condenser pressure was maintained at 1 psia (6.89 kPa) and ambient temperature was kept constant at 59°F (15°C). Figure 1 is a simplified schematic of the subcritical system studied for plant response to oxy-fuel. As can be seen, the steam on its way to the high pressure steam turbine is split into two streams to ensure that the correct steam conditions are met under varying recirculation rates. Also, this was done to study the effect of using excess steam to power the cryogenic plant. Changes made to a typical plant to fit it for the use of oxy-fuel are also highlighted. Establishing a non-nitrogen bearing combustion medium within which to burn fossil fuel is a primary requirement for realizing the benefit of oxy-fuel combustion as a low-pollutant firing technology. This would entail fitting recirculation fans to carry flue gas back to the boiler’s air intakes for reuse. An air separation unit would become a part of a typical plant using this firing method.

Method of Study

The studies being conducted by the USDOE/ARC and Jupiter Oxygen Corporation use consistent flow rates of oxygen and pulverized coal for each case studied. Oxygen concentration is changed by adding or subtracting recycled flue-gas from the combustion-supporting gas entering the boiler, and in all cases, air was excluded from the flue-gas stream. As the oxygen content changes, the thermodynamic and heat transfer behavior of the plant models change. Plant capacity and efficiency were observed for the different oxygen concentrations that resulted from varying the recirculation rates. Also, the amounts of fuel energy released via radiant heat transfer were tracked and recirculation

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rates were optimized to ensure that material limits were not exceeded. Composition of the exhaust from each oxygen concentration case was noted and applied to analysis of the pollutant removal process being developed at ARC.

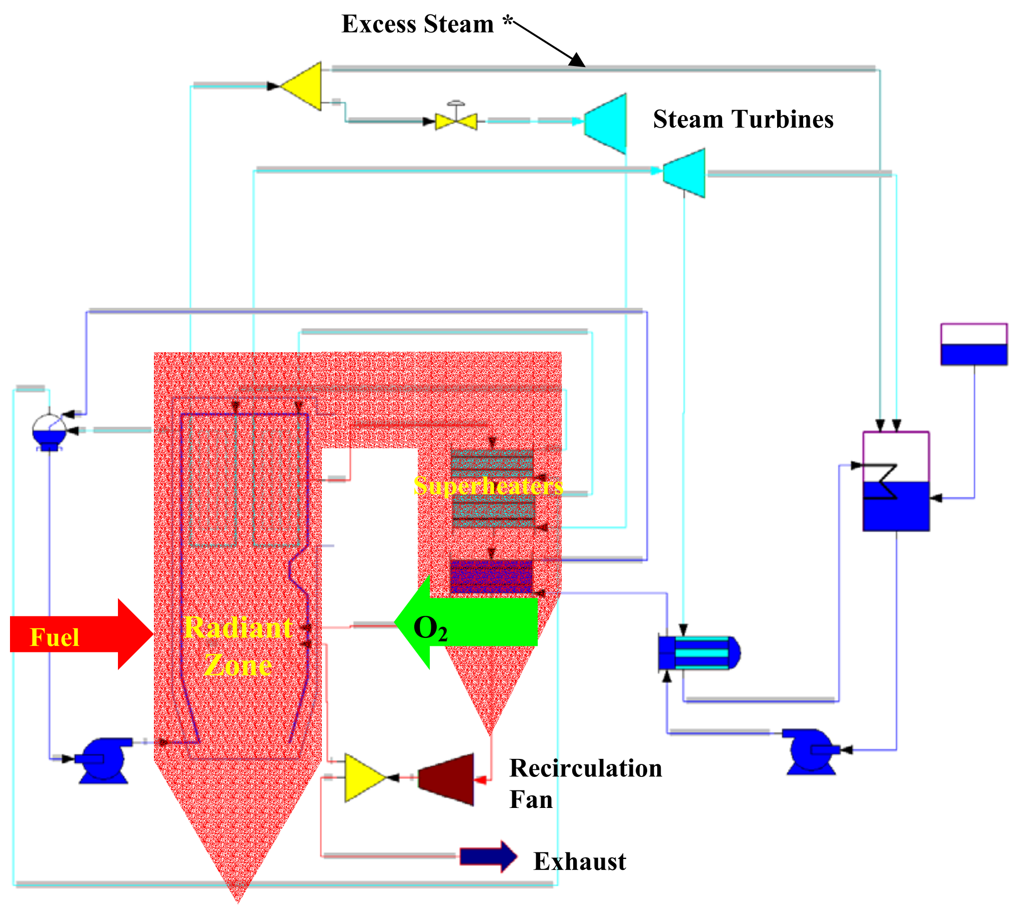

Figure 1: Changes to the boiler for oxy-fuel firing.
* Under certain modeling conditions.

Thermal Efficiency and Plant Capacity

Thermal efficiency and plant capacity were modeled for oxygen concentrations up to 45% in the combustion gas. The models showed increases in both efficiency and plant capacity above that of air, with increases in O_2 concentration to about 28% (see Figures 2 and 3). For comparison, the squares in these figures represent modeled values in air combustion.

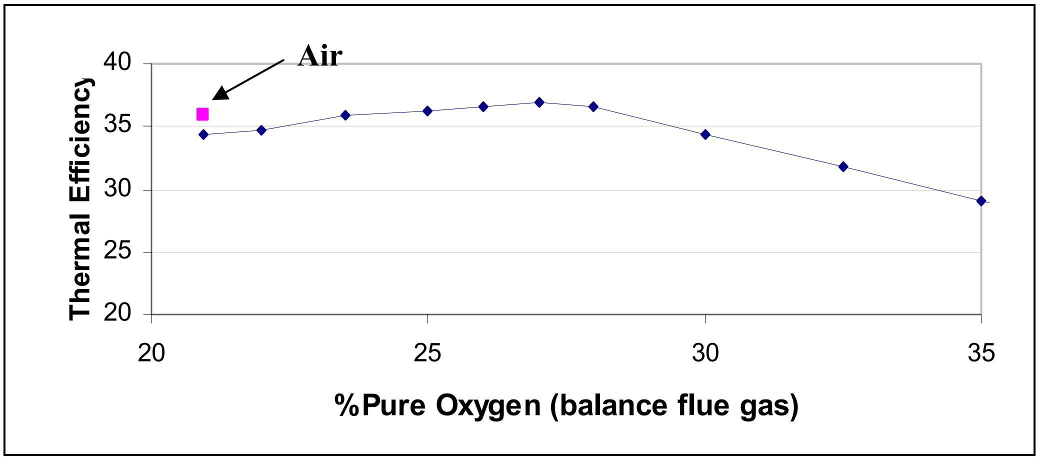

Figure 2: Thermal efficiency change with change in oxygen content

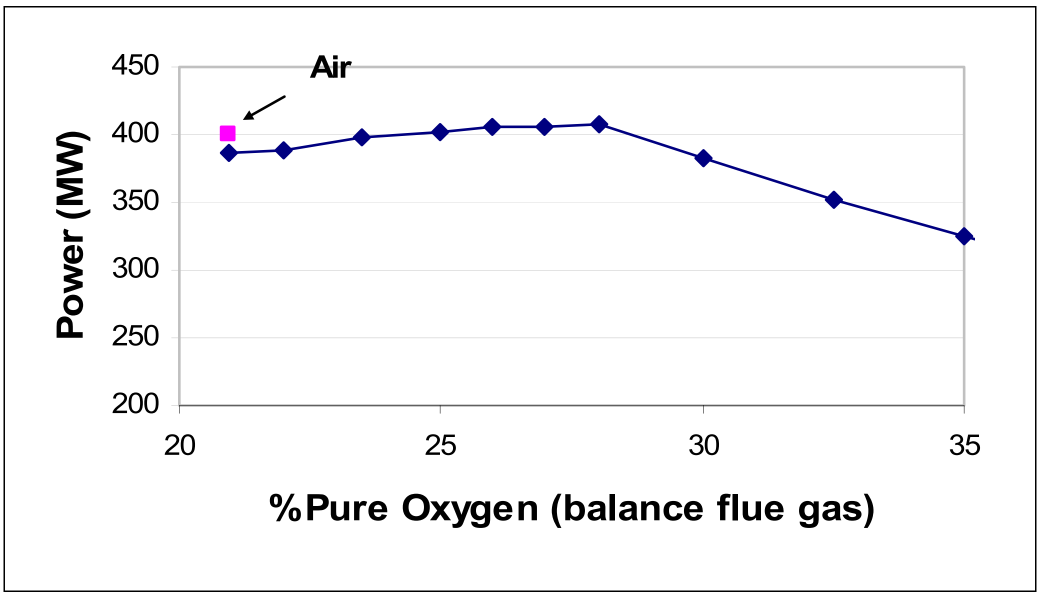

Figure 3: Capacity change with change in oxygen content

Heat Transfer with Oxy-fuel

Analysis of the changes in heat transfer characteristics resulting from oxy-fuel combustion was conducted within the power plant computer model. In the model, the heat transfer surface area was kept constant to reflect retrofitting of an existing boiler system with oxy-fuel combustion. The total duty of all the radiant heat transfer surfaces in the boiler increased as the recirculation rates were lowered. This rise is shown in Figure 4. This rise is expected as the increased relative oxygen (lower fraction of other gases) increases the brightness and temperature of the burner flame.

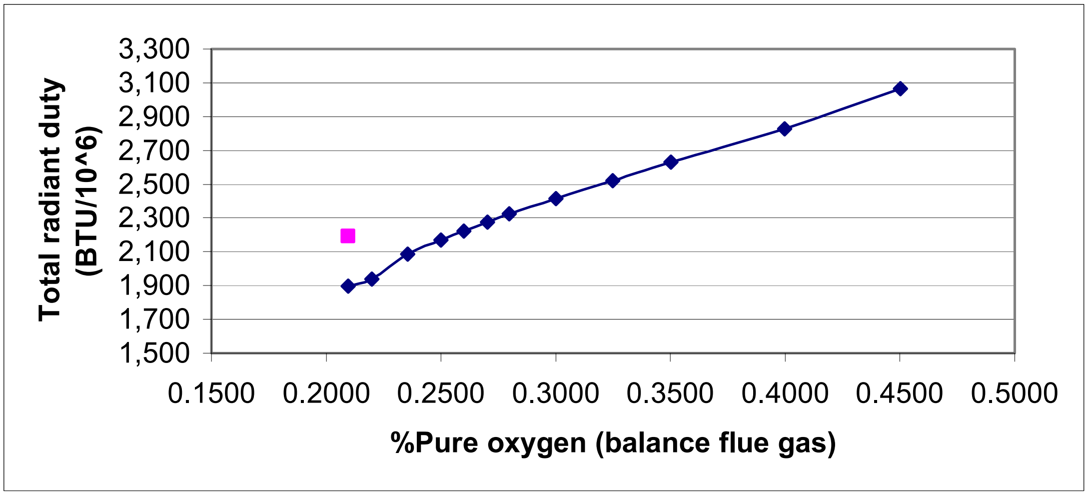

Figure 4: Total radiant duty as a function of oxygen content in combustion gas

The square in Figure 4 shows the radiant duty resulting when air (containing 21% oxygen) is used as the combustion supporting gas. The lower radiant duty given by using oxygen-enriched recycled flue gas is a function of the different infrared absorption characteristics of this "gray gas" medium. The CO_2 and H_2O cause the recycled flue gas to absorb a larger portion of the infrared radiant energy. However, the total radiant transfer increases to beyond that of air with higher oxygen fractions in the combustion gas.

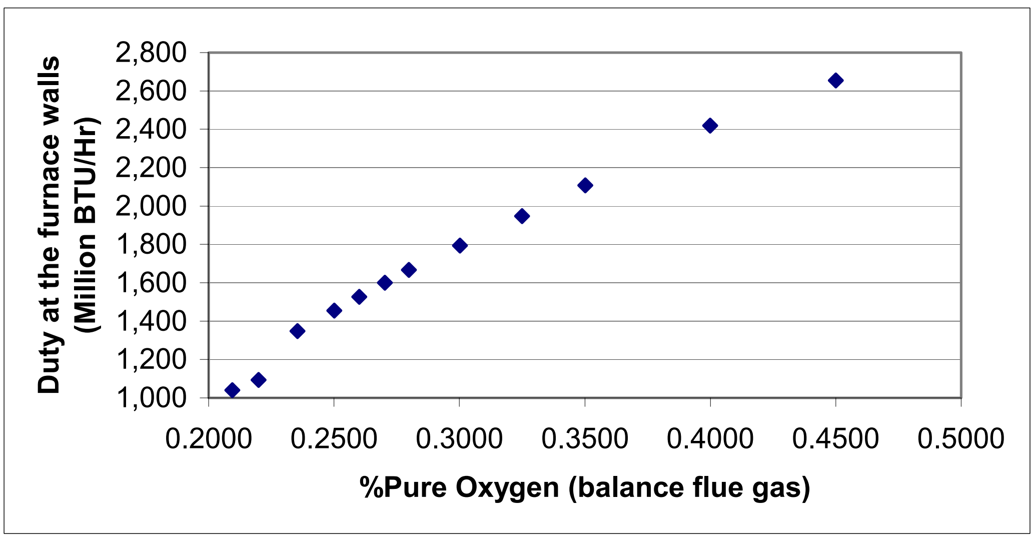

Figure 5: Boiler radiant duty as a function of oxygen content in the combustion supporting gas

The amount of heat released into the boiler walls was also modeled. Figure 5 shows that the duty at the boiler water walls rises with the relative oxygen content of the combustion gas as a result of the increase in flame temperature. The increase in duty at the furnace walls shows the release in the boiler's radiant zone of a larger amount of the finite chemical energy available in the fuel, leaving less energy in the gas available for convective transfer in the boiler's back pass. The optimal point of recirculation was determined in order to balance the radiative and convective portions so that the boiler could run under normal steam conditions. A significant portion of the modeling effort was put into the study of this effect.

When the flow of recycled flue gas is reduced to increase the oxygen content of the combustion gas, the volumetric flow of exhaust gas decreases. Initial studies of the effect of reduced volumetric flow rate (with fixed area heat transfer surfaces) on the convective heat transfer in the boiler show the expected drop in heat transfer coefficient as oxygen content increases [2].

Energy released in the radiant zone of the burner goes directly into boiling the water. An effect of combustion with increased oxygen fraction is the production of a brighter, hotter flame resulting in the release of more energy and increased duty at the boiler walls. This can have the effect of increasing the rate of steam generation in the boiler (if one desired to do so and had a beneficial use for that steam). Figure 6 shows the increase in the steam generation rate as the oxygen fraction increases. As in Figure 4, the production rate does not match air combustion until the relative oxygen in the combustion gas reaches approximately 28%. These effects are sensitive to heat transfer to the water walls and will be influenced by wall geometry, effective flame temperature, and internal and external wall tube deposits. Since the boiler studied was a ‘typical’ boiler, the modeling conditions were set up to reflect typical operating conditions.

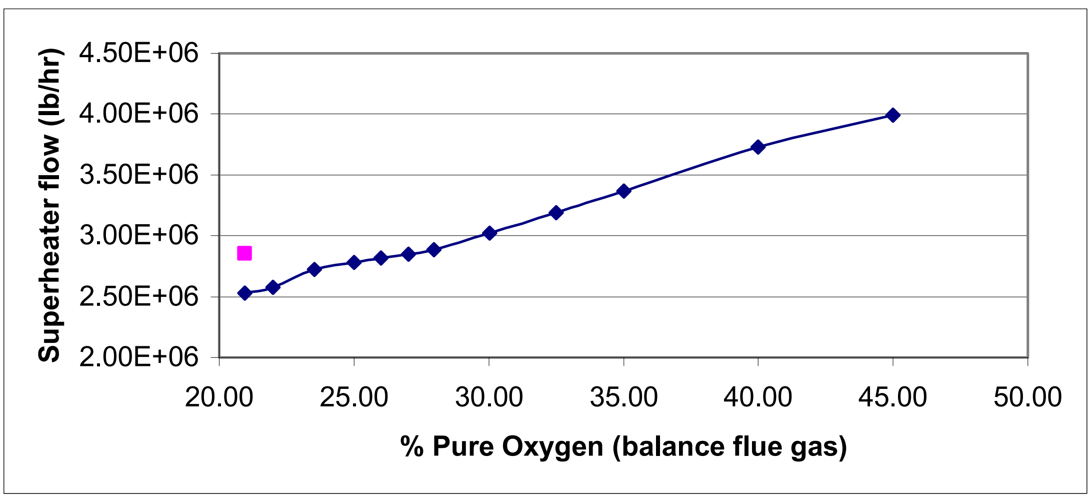

Figure 6: Superheater flow as a function of combustion gas oxygen content

When steam flow is allowed to increase, it is accompanied by a decrease in the superheat temperature. This result has been predicted in literature conversely as: “For a change in the amount of excess air entering the burner zone, there is a corresponding change in the quantity of gas flowing over the convective superheater; therefore, an increase in excess air generally raises the steam temperature.”[2] In our case: For a change in the amount of recycled flue gas entering the burner zone, there is a corresponding change in the quantity of gas flowing over the convective superheater;

therefore, as the flue gas recirculation rate increases, there is generally a rise in the steam temperature.

Since efficiency of a steam cycle increases with increased steam temperature, we expected to see difficulty in maintaining steam turbine performance as we increased the relative amount of oxygen in the combustion gas for fixed heat transfer surface areas. We anticipated that a minimum level of flue gas recirculation would be required in order to maintain superheat temperature and flow rates, as was described earlier in the model.

If this excessive steam flow were heated to the correct temperature, there still would be the problem of producing steam at a rate beyond the maximum flow for which the steam turbine was designed (as was modeled in one particular case). The excess steam must be shunted elsewhere either before or after the superheater. The excess could potentially be used for co-generation if there were a need for saturated or superheated steam. If this excess steam were separately superheated, even at a lower pressure, it could be used to power the oxygen generation plant necessary for oxy-fuel combustion.

Changes in Boiler Surface Area

The supercritical model also examined the ramifications of changes in boiler heat transfer surface area in response to changes in relative oxygen content in the combustion gas. When the model was allowed to change boiler surface area, the concentration of oxygen that could be applied to the plant in a balanced model nearly doubled. Thermal efficiency and plant capacity improved as a function of increased oxygen fraction and decreased water-wall surface area. The implication for retrofit is that, for plants with boilers whose life is coming to an end, the replacement may be a smaller boiler burning oxy-fuel and a plant capable of higher efficiencies and capacities. With the decrease in radiant surface area to offset the increased heat transfer rate in the radiant zone of the boiler, concentrations of oxygen up to 38% were modeled to continuously increase plant efficiency and capacity to up to 42% and 417 MW, respectively. For these models, the fuel input to the plant was kept constant as the fraction of oxygen in combustion gas was changed.

Flue Gas Characteristics

Compositions of exhaust from 400MW boilers (not stacks) with and without flue gas recirculation were measured, holding the percent of oxygen exiting the boiler the constant in both cases. As Table 1 shows, the mass-flow of exhaust leaving the recirculated gas boiler is higher. Fans moving this gas stream will perform more work in a recirculation system than in a once-through system. The concentration of CO_2 and H_2O in this stream are increased such that nearly 94% of the flue gas is condensable. A process being examined at the ARC treats a flue gas bleed stream comprising about 25% of the boiler output, the balance being recycled to the boiler for combustion. CO_2 and water are removed from the gas stream, and with them, particulates and SO_2. The final product is 25.85 tons per hour of a gas consisting of 91.5% nitrogen and oxygen, and 8.5% CO_2 (Table 2).

Table 1: Comparison of combustion products leaving the boiler with combustion supported by air and with combustion supported by O_2 and recycled flue gas[3].

	Combustion Supported By Air	Combustion Supported By O_2 with recycled flue gas
Flow (lb/hr)	3,539,738	4,154,215
CO_2 (vol)	0.1368	0.6085
O_2 (vol)	0.0350	0.0350
N_2 (vol)	0.7345	0.0206
H_2O (vol)	0.0829	0.3269
SO_2 (vol)	0.0020	0.0090
Ar (vol)	0.0088	0.0000

Table 2: Mass flow and composition of final plant exhaust (using combustion supported by O_2, flue-gas recirculation and integrated pollutant removal).

	Post Process Exhaust
Mass (ton/hr)	25.85
CO_2 (vol.)	0.085
O_2 (vol.)	0.5765
N_2 (vol.)	0.3384
H_2O (vol.)	0.0001
SO_2 (vol.)	0.0000

Brief description of Integrated Pollutant Removal [4]

The use of oxy-fuel combustion with recycled flue gas, coupled with liquefaction of flue gas for pollutant capture, is being examined at the ARC (USDOE, Albany Research Center). This Integrated Pollutant Removal (IPR) process is being studied through computer models and experimentation. The IPR process compresses a portion of flue gas from a fossil-fueled boiler, dissolving or otherwise entraining non-condensable pollutants and producing liquid exit streams which may then be cleaned to remove those pollutants. Because the combustion process uses flue gas recirculation, the amount of nitrogen in the exhaust to be treated is markedly lower than in exhaust from combustion supported by air. This significantly lower volume of exhaust, low in NOx and relatively high in concentrations of other pollutants (SO_2, CO_2, and Hg), also has a higher H_2O content. The lack of nitrogen in this exhaust allows H_2O and CO_2 to be economically compressed for removal and recovery or disposal.

The composition of the flue gas used for the IPR study is typical for oxy-fuel combustion using approximately 21% O_2, similar to the amount of oxygen available in air. Table 3 shows the predicted change in composition, mass flowrate and volume flowrate of the exhaust stream as it travels through the IPR process.

Table 3: Gas streams showing composition, pressure, mass- and volume-flowrate.

Gas composition is shown as mole fraction.	Exhaust Flue gas	After first H_2O condensation	After second H_2O condensation Compression 1	After first CO_2 condensation Compression 2	After second CO_2 condensation Compression 3	After third CO_2 condensation compression 4 and Expansion 1
CO_2	0.6085	0.8711	0.9143	0.7100	0.3900	0.0850
O_2	0.0350	0.0501	0.0526	0.1821	0.3830	0.5765
N_2	0.0206	0.0294	0.0309	0.1069	0.2249	0.3384
H_2O	0.3269	0.0365	0.0022	0.0010	0.0021	0.0001
SO_2	0.0090	0.0129	0.0000	0.0000	0.0000	0.0000
Pressure (psia)	15	15	180	1,200	2,500	5,000 to 2,000
Mass (lb.hr)	935,000	789,000	762,000	207,000	87,800	51,700
Flow Rate (ft^3/s)	3378.50	2945.94	150.09	6.53	1.49	0.50

Economics

By combining the use of oxy-fuel technology with the IPR system, an economically viable solution is created for the elimination of virtually all pollutants, with the exception of a small amount of CO_2, at a cost which is competitive with those traditional technologies that exist today, and are incapable of producing the same results at similar cost. Besides the improved efficiency and consequent reduction in fuel usage inherent with Jupiter's Oxy-fuel system[6] , additional cost saving could also be had by utilizing the excess steam produced in order to power the cryogenic plant which has historically been the greatest deterrent to use of oxy-fuel solutions. By consolidating the pollution control systems with the efficiency increases inherent in oxy-fuel systems, one can look at the plant in a holistic sense and see that even in a retrofit setting, its desirability from an economic standpoint as well as a technical standpoint is clear. Oxy-fuel retrofit technology today is a commercially viable alternative to providing a complete and final solution for total pollutant removal.

Conclusion

Modeling has shown that the recirculation rate can affect both the steam production and superheat temperatures. The conclusion reached in the model, showed a rate of approximately 28% (oxygen supported combustion with balance recycled flue gas, with air excluded), for optimal plant output when heat transfer surface area is held constant. Variations of the model have also revealed new opportunities to produce power using steam to offset the cost of running the cryogenic plant. This insight, along with information gathered on superheat temperatures and balance of plant equipment, indicates that retro-fitting boilers with oxy-fuel combustion is feasible.

The modeling work has supported the pilot plant testing conducted by Jupiter Oxygen Corporation, the purpose of which is to verify the suitability for wide spread use. While modeling alone does not provide a perfect picture of plant performance, it has been relied upon as a good measure and indicator of actual performance. With this in mind, the computer modeling of a 400 MW power plant has successfully shown that the application of oxy-fuel technology provides a viable alternative for pollution reduction and efficiency improvement. Since design methods for oxy-fuel systems are similar to those of conventional fossil fueled boilers, the major manufacturers of conventional boilers should be able to quickly implement this technology in both new designs and retrofits as necessary.

By combining an oxy-fuel technology such as Jupiter's with ARC's IPR, a concise plant computer model was generated to show the bottom line effects of an ultra-low emissions power plant. Together, these two technologies can realize the goals of low NOx, high efficiency, and CO_2 capture from coal fired power plants today. While a defining economic study was not within the scope of the computer modeling, other work done by members of this group and others have shown that these approaches offer a competitive alternative, and in some cases, an attractive option for pollution control.

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