Jupiter Oxygen Corporation

Developer: Jupiter Oxygen Corporation

Technology Type: Oxy-Combustion

Thermal Resource: Coal

Application: New/Repower

Technology Class: Integrated CO2 Capture

EPRI Participation: Current

Development Status: Active

Current TRL: 7

Last Updated: 12/23/2022

Introduction

Jupiter Oxygen Corporation (JOC) [1], which has developed a next-generation atmospheric-pressure oxy-combustion process, proposes to use their unique, proprietary untempered oxygen burners to produce higher burner flame temperatures with high-purity oxygen (95–100%) and lower flue gas recirculation (FGR) rates in the furnace of a pulverized coal (PC) oxy-combustion process [2]. The goal is to provide higher furnace radiation heat flux with a more uniform absorption pattern to the furnace wall enclosure to improve overall efficiency.

JOC's oxy-combustion process and burner development has occurred over a 15-year period with full scale burner testing completed in November 2022 at General Electric's facility in Bloomfield, CT resulting in technology readiness level (TRL) 7 status. Testing also occurred under at 36-month DOE program from 2015 – 2018 and prior to that testing was completed to the level of 15 MWth at JOC's facility in Hammond, IN between 2008 to 2012 that resulted in TRL 6 status. JOC has conducted an oxygen burner development program involving full-scale testing and providing engineering model studies for components and overall system, which were used to create a commercial-scale design for an existing boiler. The balance of the oxy-combustion steam generator system components and other balance-of-plant equipment required for the commercial plant would be supplied by existing vendor and aftermarket suppliers. JOC has completed a full front-end engineering and design (FEED) study to retrofit the system to an existing PacifiCorp coal-fired boiler.

Process Description

The JOC oxygen combustion system configuration, shown in **Figure 1**, is like atmospheric-pressure oxy-combustion systems proposed by other process suppliers, but with the use of the unique high flame temperature burners developed by JOC. The burner design produces more uniform heat transfer in the radiant zone due to higher radiation from the high flame temperature and the heat-transfer characteristics of the gaseous combustion products. The improved heat transfer at higher temperatures has yielded higher fuel efficiency for the process.

Significant computational fluid dynamic (CFD) modeling has been done to investigate the potential benefits of the JOC system as well as to determine if reduced FGR and higher radiation does not cause material issues. The modeling has shown that peak heat fluxes on heat surfaces are below those that would damage the metal. Testing confirmed the modeling accuracy and integrity and there was no damage or concerns with the burner or near burner components. The modeling has also shown a significant increase in radiative heat transfer from the technology at the same firing rate [3].

Particulates and sulfur are removed from the flue gas, potentially using the novel with Integrated Pollutant Removal™ (IPR) process or cryogenic based carbon capture and purification system, depending on the purity requirements of the CO_2, which limits build up and protects the fans and boiler from erosion and corrosion. The JOC process flow diagram shows another difference with other processes, as most of the oxygen is injected at the burners and the balance is mixed with the primary FGR upstream of the pulverizers for peak firing temperature control to maximize efficiency. Startup and shut down are expected to proceed in a manner like what have been demonstrated at oxy-combustion test facilities of other system developers.

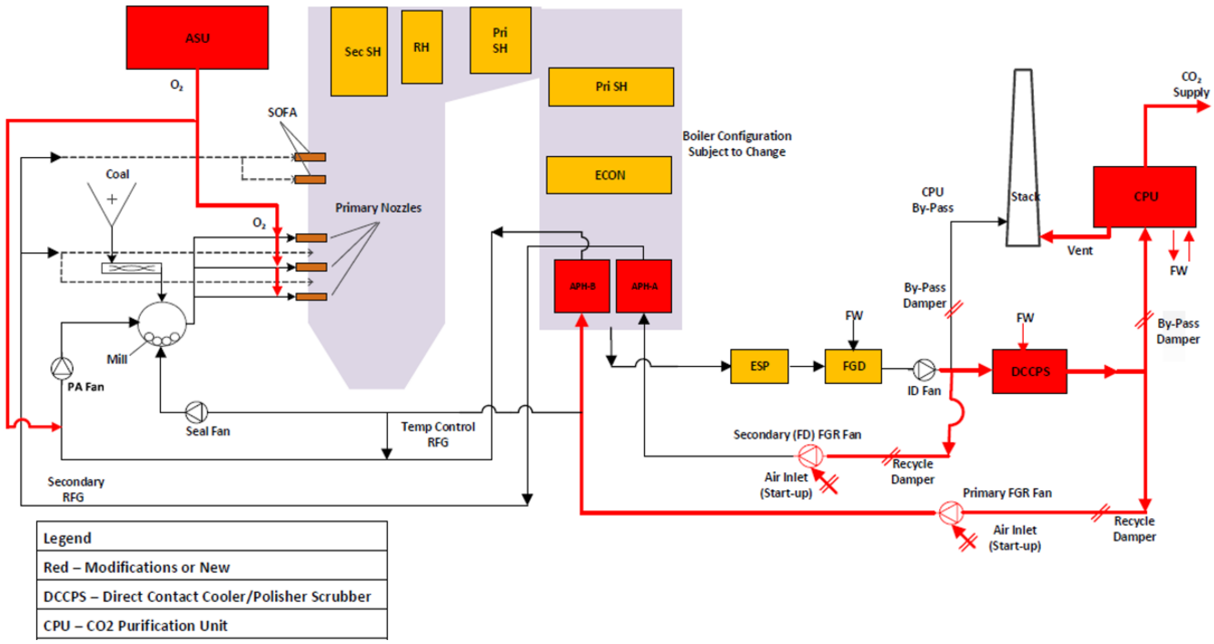

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Figure 1 – JOC's Oxy-Combustion Process Flow Diagram

The JOC system can be installed as a completely new-build, greenfield plant or can be retrofitted to an existing coal unit. In the case of a retrofit, much of the existing unit can be reused, including the steam cycle and coal handling in their entirety, existing boiler, and parts of the combustion system [4]. Oxygen production, FGR, and the CO_2 purification would all need to be added.

Technology Status

JOC, as part of a U.S. Department of Energy (DOE)-funded project, constructed a 15-MWth oxy-fuel burner test facility with IPR to test high flame temperature oxy-fuel combustion and advanced CO_2 capture [5]. The test facility, shown in photos in **Figure 2**, began firing coal with oxygen in August 2008 and completed its work in cooperation with DOE in December 2012 [6].

During the testing, combustion protocols were developed for baseline air firing with natural gas, oxygen and natural gas firing with and without FGR, and oxygen and PC firing with FGR. The focus was on characterizing burner performance, determining heat transfer characteristics, optimizing CO_2 capture, and maximizing heat recovery, with an emphasis on data traceability to address retrofit of existing boilers by directly transforming burner systems to oxy-fuel firing.

The retrofit of the JOC oxy-combustion burners to existing coal-fired plants, subcritical and supercritical, was studied by the Albany Research Center in 2005 using CFD [7]. Key findings from the analysis were:

- Models showed increases in both efficiency and plant capacity (above those of air-fired) with increases in O_2 concentration to about 28%
- FGR rates decreased, radiant heat duty to the furnace walls increased, and heat absorption to the convection pass sections decreased. Optimal FGR was determined to balance the radiative and convective portions so the boiler could run under normal steam conditions.
- The modeling 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 changed

boiler surface area, the concentration of oxygen that could be applied to the plant in a balanced model nearly doubled. Efficiency and plant capacity improved as a function of increased oxygen fraction and decreased water-wall surface area.

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Figure 2 – Photos of JOC's 15-MWth Oxy-Fired Burner Test Facility in Hammond, IN

- Reduced FGR rate on the convective heat transfer in the boiler showed the expected drop in heat transfer coefficient as oxygen content increases.

JOC was part of a team that has received a $1.25M DOE grant in June 2015 for a 36-month project entitled "Characterizing Impacts of High Temperatures and Pressures in Oxy-coal Combustion Systems." The team consisted of Reaction Engineering International, University of Utah, Praxair, and JOC. The project performed multi-scale experiments, mechanism development, and CFD modeling to generate modeling tools and mechanisms capable of describing high-flame temperature oxy-combustion to guide the development of new oxy-boiler designs [8, 9].

JOC self-funded a 36-month full scale burner test campaign with General Electric that concluded in November 2022. The test facility was configured to burn pulverized coal in both air firing and oxygen firing as shown below in **Figure 3**. Photos of the test facility are shown in **Figure 4**,

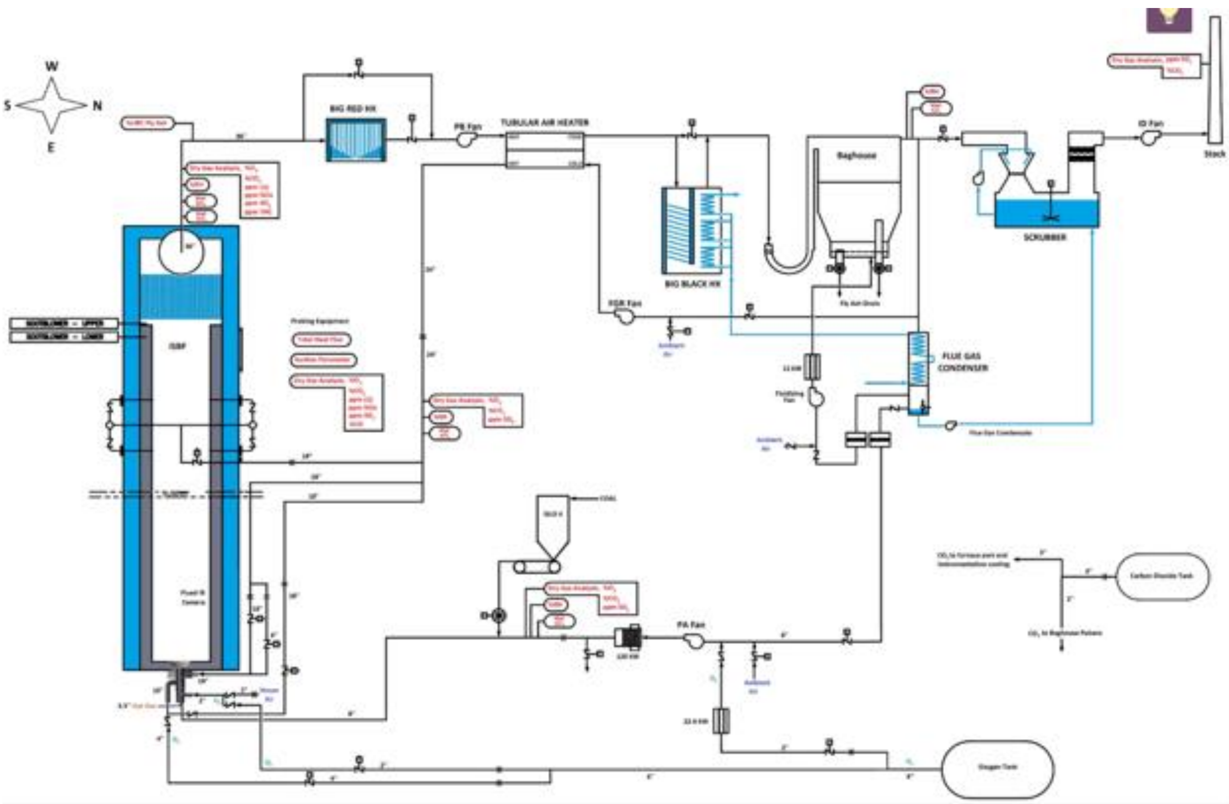

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Figure 3 – Schematic of General Electric Test Facility in Bloomfield, CT


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Figure 4 – Photos of General Electric Test Facility in Bloomfield, CT

The testing involved full load and part load operations for both air firing and oxygen firing with flue gas recirculation (FGR).

The focus was on characterizing burner performance, operating temperatures, heat fluxes and emissions.

Photos of the burner are shown in **Figure 5** and the oxy-firing burner flame profile is shown in **Figure 6**.

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Figure 5 – Photos of JOC’s Oxy-Fuel Burner

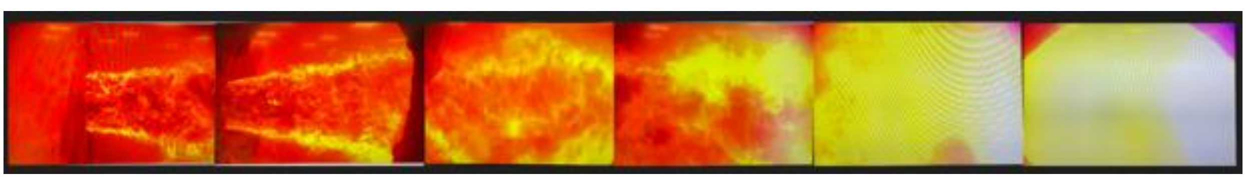

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Figure 6 – Photo of JOC’s Oxy-Fuel Burner Flame Profile

The application of JOC’s high flame temperature oxy-combustion to an existing boiler will require FGR to limit excessive temperatures and provide heat transfer performance for the existing boiler design. Furnace tube metal temperatures have been calculated for sub-critical boilers only. The highest steam conditions analyzed thus far to determine tube metal temperatures are for a drum boiler at 1600 psig (11

MPa) and 1005°F (540°C). Conditions up to 1400°F (760°C) and 4350 psig (30 MPa) are being considered for steam generators under development.

To achieve and reach the full potential and extent of the JOC claims with intended high flame temperature operation, a new or modified steam generator design may be needed that departs from current industry experience and practice.

Within the 2019 patent, the oxygen percentage in the O_2 streams is allowed to vary from 90 to 100% content, and the carrier oxygen content should be controlled within 0 to 30%. In intended operation, undiluted O_2 should be used to allow the flame temperature to reach at least 4000°F. Additionally, the fuel flow rate is controlled to be in the range of 20 to 150 ft/s, which might change due to where the flame originates within the burner. When utilizing FGR, the flowrate should be controlled such that it falls between 10 and 75 ft/s and be at least 90% oxygen. The oxygen to fuel ratio for a 100% pure oxygen operation should be 2:1 but depending on different fuel and oxygen purities can vary from 1:1 to 3:1. The highest reported peak flame temperature within supplied data is roughly 5000°F (2760°C).

As described in a 2019 patent, the oxy-combustion burner is of a quadruple annulus design, with the innermost annulus for O_2 delivery, followed by an annulus for coal, another O_2 annulus, and finally the outermost annulus for FGR. The outer O_2 feed allows for local cooling while controlling the flame. There also exists a quarl specifically designed for high temperature operation and allows for fuel and oxidant injection through a furnace wall. The quarl simultaneously provides for reduced heat flux to near-burner surfaces through surface heat diffusion, and to stabilize the flame through recirculation zones. In large part due to the outer O_2 annulus, this burner design can provide flame temperatures exceeding 4000°F without damaging burner and furnace components.

In 2020, a patent for an annular shroud burner was assigned to JOC, which involves recycling a minimal amount of flue gas to achieve the appropriate flame temperature, in theory maximizing efficiency. The oxygen-coal mixture, upon combustion, can reach flame temperatures above 4500 °F (2482 °C). [12]

Further development and modeling have recently taken place involving a team lead by JOC, which includes the organizations listed in **Table 1**, resulting in a detailed pre-FEED study for the retrofit application of the technology to PacifiCorp's coal-fired Dave Johnston's 115-MWe Unit 2 in Wyoming. The same team, along with Air Liquide, Babcock & Wilcox, and Graycor participated in a full FEED study, which was completed in July 2021.

Table 1 – Organizations Involved in JOC's Feasibility Study for PacifiCorp's Dave Johnston Plant

Organization	Role
JOC	Project developer and technologist for oxy-combustion and CO_2 capture technologies
Sargent & Lundy	Balance-of-plant engineering, project oversight, and cost estimating
Main Line Engineering	Process equipment design
Reaction Engineering International	Process and CFD modeling
Sirois Engineering	Boiler engineering services and performance, air heater modifications, and process modeling support
University of Wyoming, Enhanced Oil Research Institute	Enhanced oil recovery (EOR) assessment, CO_2 pipeline, and modeling
EPRI	Consulting and advising
PacifiCorp	Host utility

A rendering of the retrofit of the JOC technology to the PacifiCorp's Dave Johnston plant is shown in Figure 3. The project is designed to capture 97% of the CO_2 generated by the Unit 2 boiler, which will then be purified, compressed, and sold to near-by oil fields under a long-term CO_2-offtake agreement for EOR. The project will also utilize §45Q tax credits to further enhance funding and economic considerations. An added benefit of the project is that post-retrofit nitrogen oxide (NOx) emissions will be significantly reduced without the need for post-combustion NOx emissions controls. Water captured from the flue gas within the JOC system's direct-contact cooler polishing scrubber also reduces the need for makeup water. Finally, the retrofitted boiler design will also provide the ability to run on air-firing for periods when the CO_2 purification unit, CO_2 pipeline, and/or oil field is offline. Operation is planned to begin in early 2025 [10].

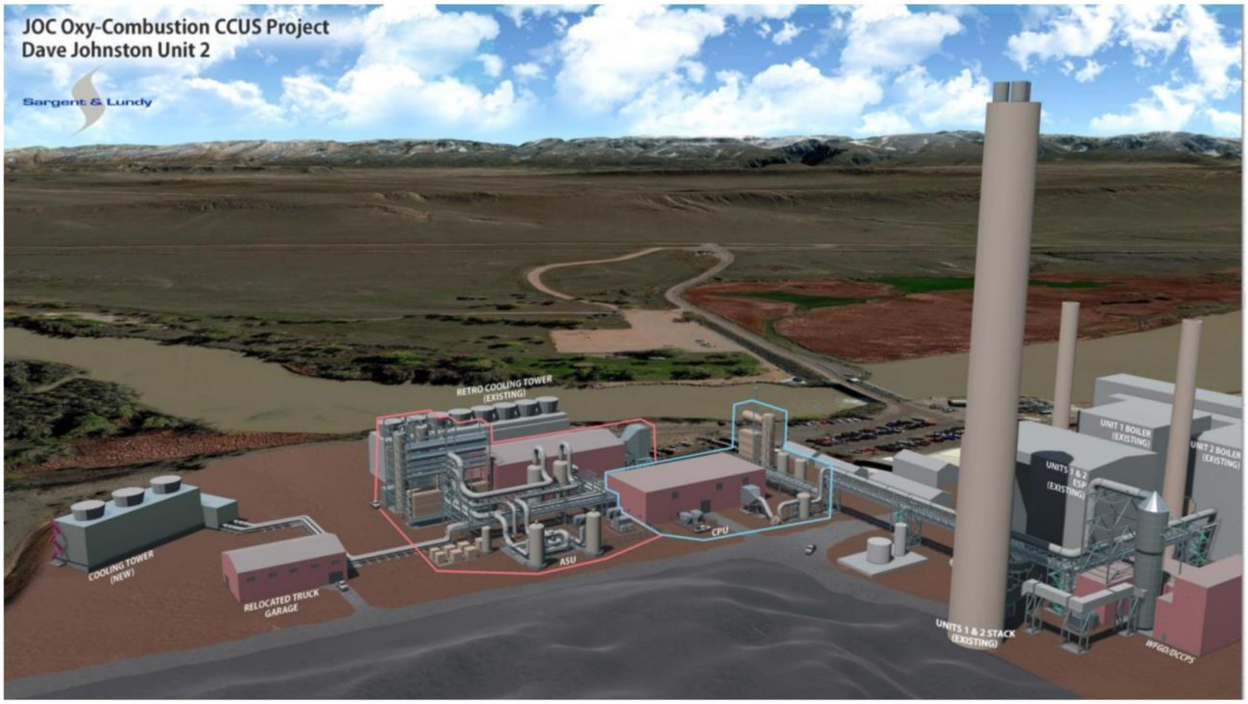

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Figure 3 – Rendering of the Retrofit of JOC's Oxy-Combustion Process to Dave Johnston's Unit 2

Benefits and Costs

The underlying hypothesis around JOC's novel oxy-combustion burners is that increased flame temperature will result in:

- An increase in the total heat transfer in the system, and in particular increased heat transfer in the radiant section, which improves boiler efficiency
- A decrease in fuel usage, when compared to other CO_2 capture approaches
- No increase in damage to boiler materials
- Reduced FGR, which in turn reduces flue gas flow and associated auxiliary power
- Water recovery of the coal hydrogen and moisture content.

The heat integration is estimated to improve overall efficiency of the JOC oxy-combustion technology by 1.5–2.1% points [11].

JOC estimates the cost of implementing their oxy-combustion technology on an existing 112-MWe unit that an in-place sulfur scrubbing system is ~$225M ($2010/kW). Economies of scale would likely improve costs for a larger plant. Thus, JOC expects the technology to be less expensive than amine-based post-combustion capture given the JOC oxy-combustion process results in an exhaust stream of highly concentrated CO_2, making the carbon capture train less complicated and less expensive than amine-based technologies as NO_x control equipment is not required [12].

JOC's aggressive commercialization strategy seeks to significantly shorten the time to full-scale deployment of their oxy-combustion technology, by leveraging design and lessons learned from their 15-MWth pilot project as well as other oxy-combustion projects. The next step is to conduct a demonstration of the JOC oxy-combustion process at a commercial-scale, operating coal-fired power plant—PacifiCorp's Dave Johnston 112-MWe Unit 2. JOC and PacifiCorp completed a FEED study in July 2021 for 6 converting the unit to high flame temperature oxy-combustion with carbon capture with the delivery of CO_2 to a nearby oil field for geologic storage and/or EOR.

Based on this strategy, with the planning and FEED study already in place for installing the system at the existing PacifiCorp Dave Johnston Unit 2, permitting, construction, and commissioning would then be finished by the end of 2025 with commercial operations slated to commence at the start of 2026. This scheduling would allow the plant to qualify for §45Q tax credits for CO_2 via EOR in nearby locations in Wyoming.

Barriers and Challenges

The following technology gaps need to be addressed:

- Through continued CFD modeling and testing, determine the minimum amount of FGR recognizing it can limit the dilution of the adiabatic energy balance, where the heat released is absorbed by the reduced mass flow rate. The energy input per unit mass is higher resulting in higher gas sensible heat content, enthalpy, and higher gas temperature. Other oxy-combustion technologies select the FGR flow rate to attain nearly the same furnace gas temperatures comparable to conventional air-firing combustion. This may limit the intensity of coal-ash slagging to prevent too much wall slagging and convection-pass tube section plugging. Too high of a furnace temperature will cause the enclosure to run wet and cause molten slag, to require tapping from the lower furnace. The furnace enclosure metals must survive the risk of failure due to overheating because of inadequate circulation design for the increased level of heat flux. The smaller margin in the approach to the design limits of the steam generator under consideration must be an evaluated risk.
- Impacts of the high-temperature, high-oxidation conditions on the JOC burner materials: corrosion, erosion, and thermal damage may occur without proper engineering. This was vetted as part of the burner full-scale testing, in which the burner performed flawlessly with no metallurgical issues or concerns.
- Scale-up issues: the JOC system has been tested at 15 MWth and the burner at full scale and is now planned to increase to 115 MWe in scale—even if the same size burner is used, interactions between multiple burners, mixing, and balancing radiative heat transfer will need to be addressed. Ultimately, the system will need to be shown to be compatible with other boiler designs including opposing wall- and tangentially-fired PC boilers.
- System operating procedures, including startup and shut down with the transition from air- to oxy-firing, and back, must be developed and demonstrated using the JOC burners. These protocols were developed and implemented as part of the test campaigns with no issues or concerns.
- Furnace circulation and coal ash melting and plugging prevention are two very important considerations for the JOC oxy-combustion technology. Preventing slagging, bridging, and fouling will also be essential.

References

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[3] "Result of High-Flame Temperature Oxy-Combustion Tests at the 15MWthTest Facility and its Application to Refineries," M. Schoenfield, B. Van Otten, and B. Adams, 5th IEAGHG Oxyfuel Combustion Conference, 2015.

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