Technical Paper
BR-1818

Commercialization of Oxy-Coal Combustion: Applying Results of a Large 30 MW_{th} Pilot Project

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Abstract

The Babcock & Wilcox Company (B&W), through its Power Generation Group, and Air Liquide (AL) have been actively involved in the development of oxy-coal technologies for power generation throughout the past decade. After successful demonstration of oxy-combustion at B&W's 1.5 MW_{th} Small Boiler Simulator (SBS) and very promising full-scale (300-500 MWe) engineering studies, B&W and Air Liquide initiated a project to scale-up the oxy-combustion technology at B&W's 100-million Btu/hr (30 MW_{th}) Clean Environment Development Facility (CEDF).

During 2007 and 2008, the technology was successfully demonstrated with eastern bituminous, sub-bituminous and lignite coals. During this demonstration project, two near full-scale burners were developed: 1) the B&W DRB-XCL® burner for oxy-firing of eastern bituminous coal, and 2) the DRB-PAX burner for oxy-firing with low-rank coals. An operating procedure for smooth transition from air to oxy-combustion then back to air-fired modes has been developed. Stable flames, attached at the burner throat, have been obtained under the oxy-combustion conditions even for the high-moisture, low-Btu lignite while heat absorption in the boiler and convection pass was maintained similar to air-blown combustion. B&W's new scrubber equipped with integrated cooling surface (patent in progress) successfully reduced moisture and SO_2 from the flue gas without the need of a large and expensive gas cooler. Following the completion of this work, the ensuing commercialization process will focus on an at-scale demonstration at a host Utility. A demonstration plant design is being developed, and will involve input from the Utilities that are members of our Oxy-Coal Advisory Group. Project economics, technical design and a near-zero emissions profile are highlighted. The paper describes the experimental demonstration results of the technology at 30 MW_{th}, and the next step in the demonstration of the B&W/AL oxy-combustion technology.

Introduction

For coal to continue to drive power generation and economic expansion across the globe in the most environmentally friendly manner, technology must continue to be developed to reduce coal plant emissions to near-zero. Current technologies to control emissions of sulphur oxides, nitrogen oxides, particulate matter and, more recently, mercury are still driving towards higher levels of removal efficiency. Historically, ever-tightening emission constraints on coal-firing across different regions of the world have driven new technology developments. With CO_2 emissions becoming a regulated emission in North America and Europe, new technologies to capture CO_2 are under development, which will also benefit from further improvements in today's boiler and emission control technologies.

Oxy-combustion has a leading role in the development of carbon capture technologies for coal-fired power plants with its Near Zero Emissions Plant (NZEP) profile. Storage technology programs underway in North America and Europe have shown promising geologic potential, but larger scale and longer term injections are still needed to satisfy regulators and the general public.

Brief history / background

B&W's entry into the oxy-fuel combustion technology arena started more than a decade ago with activities that have placed B&W on a technical readiness path to support a commercial-scale demonstration.[1] Funded in part by the U.S. Department of Energy (DOE), pilot-scale development at B&W began in 2000 and in collaboration with Air Liquide (AL)[2,3] by burning eastern bituminous and sub-bituminous coals in B&W's 5 MBtu/hr (1.5 MW_{th}) Small Boiler Simulator.

Several techno-economic studies were also undertaken including one by B&W for the Canadian Clean Power Coalition in 2001, another by Air Liquide and B&W with Worley-Parsons for DOE in 2005-2006,[4] and a B&W evaluation of various capture alternatives from an investment perspective.[5] In 2007, B&W was approached by SaskPower requesting an engineering evaluation of oxy-fuel for a new 300 MW_e plant in Saskatchewan, Canada. In support of the SaskPower opportunity and other interested utilities, B&W and Air Liquide embarked upon the largest scale demonstration of oxy-fuel combustion in 2007 by modifying an existing 100 MBtu/h (30 MW_{th}) test facility, B&W's Clean Environment Development Facility (CEDF). The modifications were completed in late summer of 2007 and the first full oxy-fuel operation was achieved on October 8, 2007. Further testing with a high-volatile bituminous coal was completed by year's end. In 2008, new test campaigns were initiated with sub-bituminous Powder River Basin coal and lignite.

Large pilot (CEDF) testing

After successful testing at the 1.5 MW_{th} SBS,[4] B&W and AL moved to demonstrate oxy-coal combustion technology at B&W's 30 MW_{th} CEDF located in Alliance, Ohio. The objectives of this project were to demonstrate the following main elements:

- Near-full-scale burner fed directly by an in-line pulverizer. Pulverizer performance is affected by flue gas composition and may require more recycle gas than air to maintain acceptable performance, especially with low-rank coals.
- A new burner design for low-rank coals
- Various coal ranks including: lignite, sub-bituminous, and bituminous
- B&W's novel concept for controlling flue gas moisture and SO_2 content via a wet scrubber with integrated cooling
- AL's concept of O_2/flue gas mixing known as Floxynator™
- Effect of oxy-combustion on combustion stability, emissions including SO_2, SO_3, NO_x, CO, and Hg, furnace heat transfer, furnace exit gas temperature, and unburned combustibles
- Electrostatic precipitator (ESP) performance
- Optimization of transition methodology from normal coal combustion with air to oxy-combustion

Experimental facilities The CEDF facility has been used for more than a decade to develop near-full scale burners and other environmental technologies. The detailed descriptions of the CEDF modifications, for oxy-combustion, have already been reported elsewhere.[6] A summary of the facility description pertinent to the results is explained here.

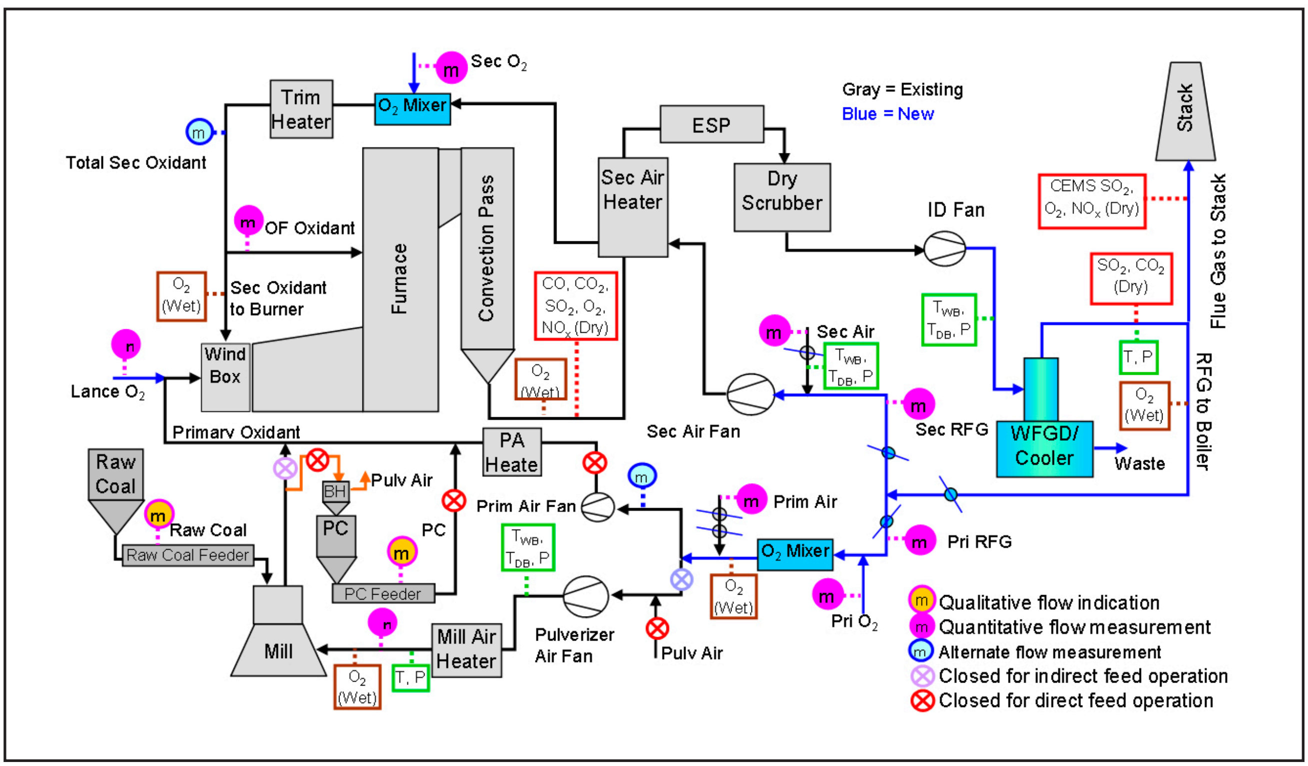

Fig.1 CEDF oxy-combustion equipment and instrumentation.

Figure 1 shows the CEDF in an oxy-firing mode. A wet scrubber with integrated cooling surface (patent in progress) was used to cool down the recycle gas before it was mixed with oxygen and recycled to the primary and secondary oxidant streams. The CEDF is equipped with a B&W pulverizer with a rated capacity of 12 tons/hr. An indirect coal feed system was used with bituminous coal at 4 tons/hr and was modified for sub-bituminous and lignite testing, firing up to 7 tons/hr.

For these tests, a DRB-XCL® burner was used for bituminous coal and a new DRB-PAX burner was designed for lignite and sub-bituminous. Each burner was equipped with flexible vanes for the secondary oxidant. Liquid oxygen was delivered to the test facility and stored on site in a 52,000-gallon oxygen tank. The liquid oxygen is vaporized with ambient vaporizers. The oxygen is regulated to an appropriate pressure and delivered to the test area via stainless steel piping. The unit has two complete gas analysis systems consisting of gas analyzers for O_2, NO_x, CO, CO_2, and SO_2 measurements at the convection pass exit and stack. The stack flyash can be isokinetically sampled and analyzed for carbon content to determine carbon utilization in the system. Mahoning #7, an eastern bituminous coal, Black Thunder, a western sub-bituminous coal from the Powder River Basin (PRB), and lignite from the Shand mine in Saskatchewan, Canada, were tested. Table 1 shows the fuel analyses.

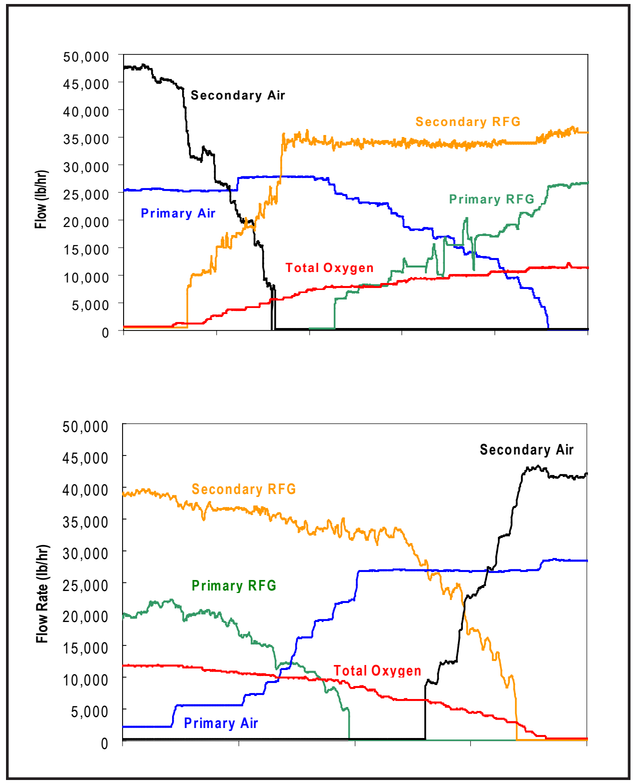

Fig. 2 Transition from air to oxy-combustion and back to air.

Results

Oxy-combustion switching, operation and flame shape in O_2/CO_2 environment The feasibility of switching from air to O_2-enriched recycle gas (oxy-combustion) operation has been demonstrated, and an operating procedure for smooth transition from air to oxy-combustion then back to air-fired modes has been developed. Figure 2 shows the transition from air to oxygen. In a step-wise controlled operation, primary air and secondary air are substituted by recycle gas and oxygen (or vice versa).

The oxy-firing flame was adjusted via burner hardware and oxygen input to obtain a stable and attached flame. The flame stability and shape were strongly dependent on the oxygen concentrations in the primary zone and coal and recycle gas moisture contents. In these tests, the overall mass flow rates of combustion gases through the boiler were similar for the oxy-combustion and air-blown conditions. The oxy-combustion flame length was the same or shorter than normal air-blown combustion.

Emissions The oxy-combustion emission levels were all lower (SO_2 the same) than emissions under air-blown combustion for all fuels and were dependent on the firing conditions. For example, the NO_x emissions were approximately 50% lower in oxy-combustion conditions than the baseline for lignite (see Figure 3). Figure 3 also shows that recycle gas moisture concentration varied from 5% to 20% which significantly changed the flame shape, but the NO_x emissions were not affected after optimum conditions were obtained via burner hardware adjustments.

The NO_x emissions were affected by pulverizer operation. Oxy-combustion affects the flow rate of the primary oxidant through the pulverizer due to its higher molecular weight than air which required more primary flow rate on a mass basis. However, the higher molecular weight of oxidant aided the pulverizer minimum velocity since the momentum of the gas is higher. Pulverizer threshold tests were performed with air and oxy-firing conditions of the CEDF. These tests started from a high primary oxidant flow rate and gradually reduced the oxidant while maintaining a constant coal flow rate until coal was rejected into the pyrite hopper or ignited coal particles were observed in the pyrite box. The rotary

Table 1
Coal Proximate and Ultimate Analyses

	Mahoning 7	*Black Thunder*	*Shand*
	Eastern Bituminous	*Western Sub-Bituminous*	*Lignite*
C	*73.30*	*50.66*	*39.62*
S	*1.37*	*0.33*	*0.51*
H	*4.97*	*3.58*	*2.54*
H2O	*4.73*	*27.43*	*34.19*
N	*1.52*	*0.65*	*0.54*
O	*6.62*	*12.13*	*10.18*
Ash	*7.49*	*5.22*	*12.42*
Total	*100.00*	*100.00*	*100.00*
HHV, Btu/lb	*13,124*	*8,758*	*6,495*

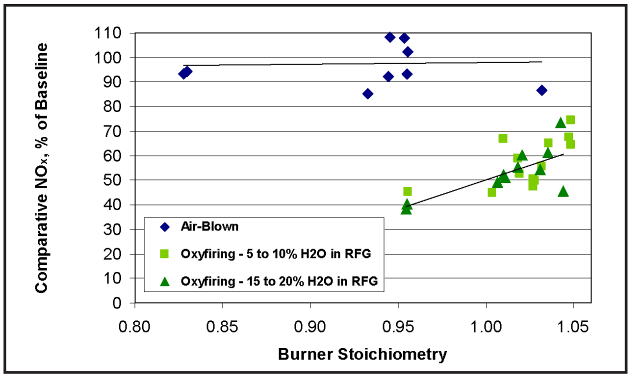

Fig. 3 NO_X emissions for lignite.

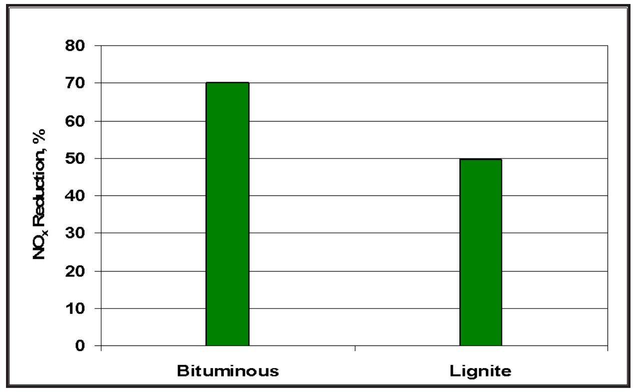

Fig. 5 NO_X reductions.

classifier was adjusted to obtain a nominal grind size of 70% through 200 mesh. Figure 4 shows the pulverizer threshold results with three coals. Baseline and oxy-combustion tests were performed at a nominal rate of 5 tons/hr and 6 tons/hr of coal input for sub-bituminous and lignite. The mill was operated with the bituminous at 10 tons/hr (close to its rated capacity) with air. The mill was used in an indirect mode for oxy-combustion tests with the bituminous. Figure 4 shows that the oxy-combustion pulverizer threshold was lower than normal air-blown combustion. However, the pulverizer inlet volumetric flow rate was almost the same or slightly lower for oxy-combustion. Figure 4 also illustrates the PA/PC [lb of air (oxidant) per lb of coal] for bituminous coal which is, as expected, low, but much higher for sub-bituminous and lignite since the mill was operated at much lower than its rated capacity. Figure 5 shows the NO_X reductions with two coals. The NO_X reductions are highest for bituminous coal and less for lignite. As discussed, PA/PC is a major factor along with other variables such as fuel volatile matter and nitrogen content as well as flame temperature.

In general, emission characteristics of oxy-combustion were favorable to air-blown combustion for all three coals tested. CO could be very high with oxy-combustion in a non-optimized situation but CO emissions were mostly lower in oxy-combustion when oxygen was introduced in an appropriate fashion. Unburned combustibles were typically low for air-blown and oxy-combustion in optimum conditions. SO_2 concentrations were kept below the facility permit and SO_2 levels were essentially the same for air-blown and oxy-combustion conditions.

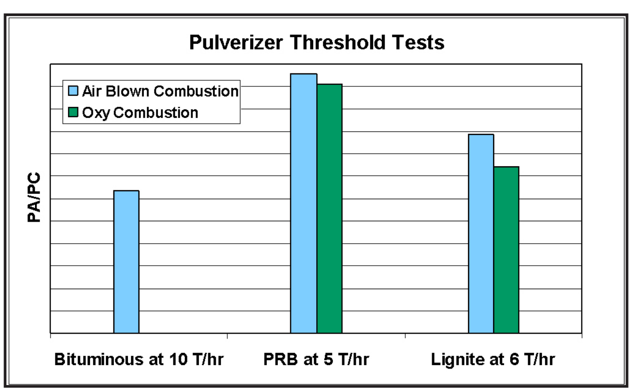

Fig. 4 Pulverizer threshold.

CO_2 emissions are affected by air infiltration to the boiler, ducts and flues where the pressure is below atmospheric pressure, notably in the boiler back-end and in the vicinity of primary and secondary fans. The boiler was operated slightly positive to eliminate air leakage to the boiler. To investigate the sources of air in-leakage, oxygen measurements were performed in the back-end of the boiler showing about 5% infiltration of air between the convection pass outlet and ID fan exit. Another large source of the air in-leakage was found to be the pulverizer air fan that was not air-tight. The total air in-leakage was approximately 10%. The CO_2 concentrations achieved in the CEDF with three coals ranged from 59% to 65%. CO_2 concentration was higher with bituminous coal than sub-bituminous and lignite because with bituminous, an in-direct firing system was used that includes a much smaller primary fan. Figure 6 shows the comparison of CO_2 via Aspen simulation and experimental results. Aspen simulations used the measured air infiltration, oxygen, recycle gas, and coal flow rates to determine the resulting CO_2 concentrations. After a good agreement was obtained, air infiltration was reduced to evaluate its effect on the CO_2 concentration. The figure shows that if we can eliminate the primary fan infiltration, the CO_2 level could be as high as 80%.

The oxy-combustion process requires large amounts of oxygen to be mixed with flue gas (> 5,000 tons/day). Since flue gas contains impurities such as ash and unburned carbon particles, special attention is required to achieve safe mixing. The Floxynator was developed to ensure safe mixing

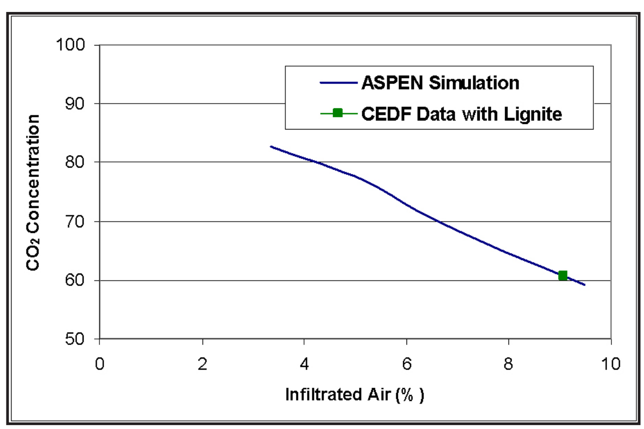

Fig. 6 Air infiltration.

of oxygen in the center of the duct, keeping the walls from higher concentrations of O_2. Since the flue walls can be maintained at normal or lower concentrations compared to air, no special considerations are required because of oxygen introduction. As shown in Figure 7, oxygen is injected radially with swirl. The momentum of oxygen is maintained in such a way that O_2 diffuses and mixes with the flue gas before the jets reach the wall.

Another unique feature of the Floxynator is its very low pressure drop design. This enables the use of a low power consuming, low pressure air separation unit (ASU) for oxy-combustion application. After developing significant expertise on gas-to-gas mixing through bench-scale tests and fluid dynamics simulations, Floxynators were designed and tested at the CEDF. At this test facility, 150+ tons/day of oxygen are mixed with flue gases. Figure 8 shows the contour plot of the oxygen concentrations at the end of the mixing duct obtained at the CEDF tests. Today, with the aid of validated CFD models, AL can design the Floxynators for commercial power plants that are required to mix 5,000+ tons/day of oxygen.

Process and cost optimization study

Recently, B&W and Air Liquide have made improvements beyond other reported oxy-combustion system designs. Novel integration of heat within the ASU, compression and purification unit (CPU), boiler and steam systems, reduced-size environmental equipment and other process improvements have lowered the levelized cost of electricity (LCOE) as compared to first generation processes as published by the U.S. DOE.[7]

In a comprehensive effort by B&W and Air Liquide in 2008, several process configuration and heat integration options were studied to 1) improve oxy-combustion performance and economics, 2) identify the strengths and weaknesses of several equipment and process configuration options, and 3) quantify the performance and economic impact of these variations.

Twenty-five variations in process and equipment were analyzed using HYSYS, an Aspen product, and a plant cost model was developed in the same detail and format as

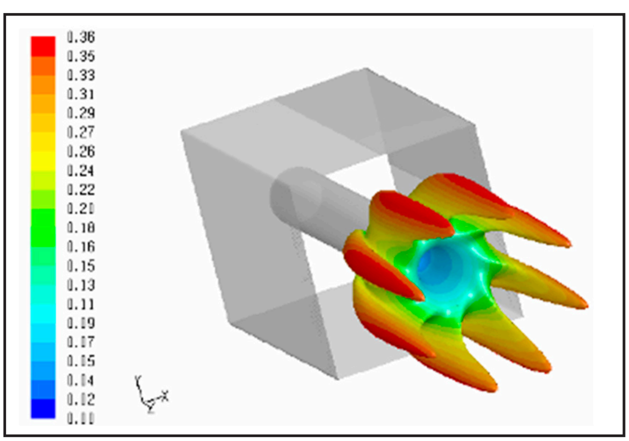

Fig. 7 Numerical simulation of Floxynator™.

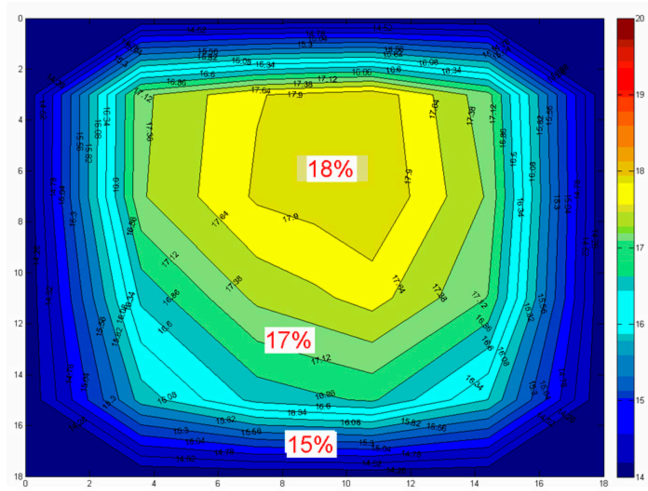

Fig. 8 Floxynator™ performance at CEDF.

provided in the DOE study. The key configurations studied included cold recycle, warm recycle, hot recycle and reduced recycle. In addition, wet and semi-dry flue gas desulphurization configurations were evaluated to determine cost and performance differences under the same conditions for either bituminous or sub-bituminous coals. The ASU and CPU were internally optimized, the heat of compression was upgraded and utilized in the feedwater cycle and to preheat oxygen, and measures were employed to minimize loss of oxygen in the process.

In the process of this study Air Liquide also optimized the ASU and CPU designs for oxy-combustion and was able to substantially reduce the power requirement for a modest increase in capital cost. This power savings was a major step toward improving the LCOE.

The results for warm recycle in comparison to the other cases developed or cited in the DOE Final Report[7] showed an improvement in LCOE of 15% over the base (case 5) SCPC oxy-fired configuration. This includes corrections to the original report which the DOE is reviewing. Compared to SCPC MEA and IGCC cases, the improvement in LCOE is 10-16%. Since the capital cost was about the same, this improvement is due to the significant improvement in net plant heat rate.

Moisture is another consideration with either warm or hot recycle. The higher moisture content in sub-bituminous coal and the lack of moisture removal in the secondary stream may affect combustion. Though the CEDF testing with high moisture sub-bituminous and lignite proved the ability to achieve good combustion at high moisture levels, additional testing is being conducted in October-November 2008 to further refine the burner design and operating parameters under warm recycle conditions and sub-bituminous coal.

Oxygen system advancements and advantages

The main characteristics of the ASU for oxy-coal combustion are: low oxygen purity, low pressure (between 1.3 and 1.7 bar abs), extra low power consumption, and large size (typically beyond 8000 tpd for industrial-scale plants using multiple units).

Low oxygen purity means a value in the range of 95-97% O_2 content compared to the typical 99.5% O_2 content of the high purity content normalized to 100 in energy scale. This allows significant savings in power consumption in the ASU as shown in Figure 9.

The cycles for the production of low purity oxygen at 95% were extensively developed at the beginning of the 1990s essentially for blast furnace vent oxygen enrichment and other applications. At that time, Air Liquide designed several plants for those applications and demonstrated specific energy of separation around 200 kWh/t of pure O_2 when the valuation of power was high.

More than 70% of the ASUs of this type in operation today are using Air Liquide technology. In addition, Air Liquide has significant experience in design, construction and operation of ASUs integrated with power plants.

For low pressure, the cycles developed in the 1990s were not fully adapted for oxy-combustion. For example, they were optimized to produce relatively high pressure oxygen (from 5 bar abs to 80 bar abs) and in some cases to perform a co-production of nitrogen. This is why a new development program was launched in 2007 to develop an ASU optimized for oxy-combustion. The idea was not to fully redesign an ASU but just to adapt the process cycle to the specific requirements of oxy-combustion (i.e. low oxygen pressure, no nitrogen requirement) and also to include technology improvements that have been demonstrated for other ASUs since the beginning of the 1990s. This has significantly improved the performance of the ASU from 200 kWh/tonne to 180 kWh/tonne.

This typical curve (Figure 10) shows that by increasing the capital expenditure by 25%, it could be even possible to further decrease the power consumption of the ASU by 10% (for example from a specific energy of separation of 160 kWh/metric tonne to reach close to 140 kWh/tonne) or to decrease the capital expenditure by 15% by increasing the power consumption by 10%.

With large size, the very nature of oxy-combustion, replacing air with nearly pure oxygen, requires large air separation plants that challenge the capability of most suppliers. Air Liquide has always owned the world size record for a single train ASU. Today's record is held by the AL ASU at SASOL in South Africa (2 x 4,300 tonnes/day). Today's Air Liquide technology allows proposals of single train ASUs up to 7,000 tonnes/day. However, because of logistics constraints, the practical size may be limited in most cases to 5,000 tonnes/day.

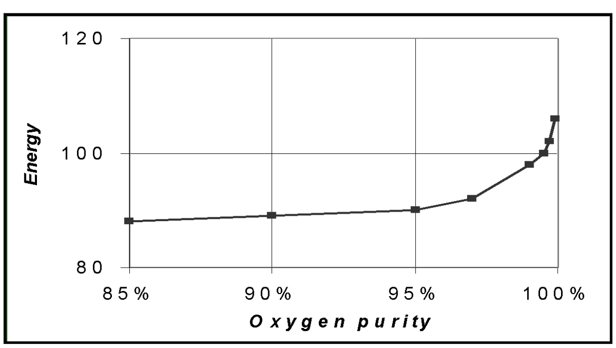

Fig. 9 ASU power requirement.

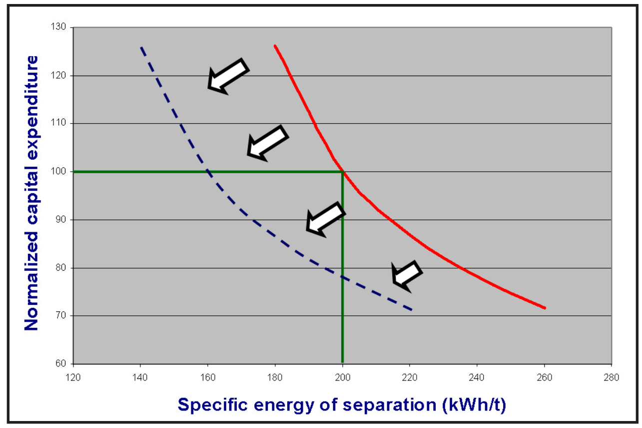

Fig. 10 Tradeoffs of CAPEX and OPEX in ASU design.

CO_2 compression and purification unit advancements and advantages The CO_2 Compression and Purification Unit is designed by Air Liquide specifically to process the flue gas emissions to provide a CO_2 product stream at a specification suitable for the demonstration of CO_2 transportation and storage underground in a saline formation, based on current knowledge of the subject.

As such it is a first of its kind. However, extensive knowledge of similar processes and the fundamental process as well as their considerable understanding of oxy-coal combustion and its flue gas product have led to a reliable and predictable design that is ready for commercial scale demonstration.

A 10,000 hour detailed engineering and cost study (FEED) for the SaskPower project (500 MW) was performed in early 2007. This experience was a unique opportunity for Air Liquide to gather effective project experience on CPU detailed design and integration in a power plant.

The CPU is designed to process the oxy-coal flue gas stream to achieve 92.5% capture efficiency with a purity of greater than 99% and a pressure of around 2538 psia (175 bar abs). The design is optimized to minimize the power consumption per ton of flue gas processed, similar to the way the ASU was optimized as described previously. In addition, the heat of compression from the compressors is integrated into the steam cycle.

Commercial scale demonstration

The next phase for oxy-combustion technology is large scale demonstration to complete the final step to commercial deployment. The B&W/Air Liquide team is ready for this step, built on a foundation of engineering design and R&D testing over the last several years.

To deliver the first commercial oxy-combustion units before 2020, large scale demonstrations need to be deployed immediately. Currently, B&W is actively pursuing projects and partners for demonstrating CCS with oxy-combustion in the range of $50MW_e$ to $150MW_e$. This size provides for commercial scale testing of all processes and equipment and will also generate up to 1 million tons/year of CO_2, an amount many believe necessary to adequately demonstrate geologic storage.

Efforts are underway both in the U.S. and abroad to further oxy-combustion development. Since all the CO_2 from the power plant is concentrated by use of oxygen rather than air to enable the combustion of coal and the CO_2 is cleaned and removed, a demonstration will require a complete plant in the size range of 50 to 150 MW_e gross. Once a plant of this size is constructed and demonstrated, then larger, commercial-scale deployment plants will follow. Thus, the step-wise approach for oxy-combustion technologies involves building units in progressively larger sizes, while seeking additional cost reductions via lower cost oxygen systems and development of improved boiler materials. This will allow oxy-combustion systems to operate within higher boiler temperatures to further increase efficiency and power plant output. Also, it may be possible to eliminate costly systems that are currently used for nitrogen oxides emissions control by optimizing the combustion process in an oxy-coal system.

Conclusion

Oxy-combustion (oxy-coal) does not involve inventing or applying new technologies to achieve its goals; it is a process integration application. Replacing the air for combustion with a mixture of nearly pure oxygen and carbon dioxide allows the boiler and environmental equipment (most directly affected) to be designed and operated in a normal manner. Recycling flue gas back to the boiler is a proven concept, and in this case simplified because the flue gas is cleaner and cooler. The addition of oxygen is provided by industry-proven air separation units. No steam turbine modifications are required for extractions, and no new turbine technology is required. The environmental control equipment operates as normal, no additional solvents or chemicals are required, and no new waste streams are generated. This leads to a near-zero emissions plant (NZEP).

The ability to constantly improve the cost of producing electricity is based on the plant process employed and its ability for improvement based on the rate of adoption (learning by doing, supply chain development, and scale efficiency) and the rate of technological progress. The former carries with it a risk premium on the initial plants that are deployed until the rate of adoption flattens that cost (risk) curve, and the latter brings process improvements and enhancements. The rate of adoption will be steep for oxy-coal due to the nature of utilizing known technologies and an already existing supply chain. The cost should decrease rapidly to its minimal level, and as scale efficiencies are realized a suite of economic sizes will be available. The rate of adoption and reductions for coal gasification and CO_2 scrubbing may be much slower due to the uniqueness, complexities and degrees of integration with the turbines that are required. The technological progress for oxy-coal has a multiple path potential which includes increased scale efficiency for ASUs, improved compression/pump systems for the CPU, innovative separation technologies for the CPU, increased steam cycle efficiencies for the boiler/turbine, novel environmental equipment control schemes, reduced water consumption, and optimal recycle rates and boiler sizing.

Acknowledgements

The authors acknowledge many B&W and AL employees including H Sarv, J Warchol, A LaRue, B Sakadjian, S Hu, R Bailey, T Flynn, N Moen, R Lenzer, K McQuistan, D Devault, D Zeng, C Periasamy, V Gautam, K Robinson, and S Levesque for the performance of CEDF tests.

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