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Technical Paper

Control of Pulverized Coal Oxy-Combustion Systems

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Presented to:
17th Annual Joint ISA POWID/EPRI Controls & Instrumentation Conference
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Abstract

With the vast reserves of coal that exist in the world, coal will continue to be a prime source for electricity generation for the foreseeable future. However, fossil fuel combustion is a major contributor to the greenhouse gas emissions which is of increasing concern. Continued use of fossil fuels for electrical generation will require reduction of these emissions. While part of this reduction will be achieved through more efficient power plants that reduce the emissions per unit of electricity produced, capture and use or sequestration of CO_2 emissions from utility boilers appears to be required to achieve the targeted reductions. A potentially more efficient and less costly alternative to Integrated Gasification Combined Cycle (IGCC) plants under development for this purpose is Oxy-coal combustion. In this concept, oxygen mixed with recycled flue gas replaces the normal combustion air resulting in a flue gas that consists primarily of CO_2. The concentrated CO_2 stream reduces the cost and energy requirements needed for its capture and sequestration. The control of the oxygen to the combustion process, recycled flue gas flow, and impact on other processes such as heat transfer in the boiler and gas stream constituents offers a unique set of control requirements which will be discussed.

Introduction

Coal, while it is the most abundant domestic fuel and remains the lowest cost fuel for power generation, is under attack based on the concerns for the impact of carbon dioxide (CO_2) on global warming. Coal is the most carbon intensive fuel which makes the development of an economical means of carbon management critical to ensure coal's continued use.

There are a number of technologies under consideration to address the capture of CO_2 from the combustion of fossil fuels. They are all dependant on the successful development of means to safely store or dispose of the CO_2. A modern coal fired power plant with a heat rate around 8600 Btu/kWh produces about 1,750lb of CO_2 per MWh which must be captured. Unfortunately, the CO_2 exists in the flue gas at only about 15% by volume wet.

There are currently three technologies which are considered as the front runners for CO_2 capture:

- Integrated Gasification Combined Cycle (IGCC) where coal is gasified, the CO from the gasifier converted to hydrogen and CO_2 by a water shift reactor, and the hydrogen is burned in a gas turbine combined cycle plant.

- Oxy-coal combustion where pulverized coal is combusted with oxygen rather than air producing a concentrated CO_2 flue gas which can then be captured.

- Amine Scrubbing where a regenerable sorbent-catalyst is used to capture CO_2 from the flue gas.

IGCC is applicable only to new construction while Oxygen Combustion and Amine Scrubbing have the potential for retrofit to existing pulverized coal fired plants.

Only Oxy-coal combustion is based on equipment and systems that are already in commercial use at the required scale. While some operational issues remain to be proven at large scale, oxygen combustion and the major operational processes have been demonstrated at pilot scale.

At this time, Oxy-coal's greatest challenge is to reduce the capital and power cost associated with the oxygen supply and the CO_2 compression. Recent work on integrating the cryogenic process with the power island needs and conditions has resulted in cost reductions but additional opportunities remain.

Even with these significant cost penalties, recent studies have shown oxygen combustion as being competitive with the other technologies and, since it is largely based on conventional equipment, likely to have a considerably lower operational risk. Figures 1 and 2 show results of recent studies by the U.S. Department of Energy[1,2] indicating oxygen combustion as the lowest cost solution for coal. In the figures, SC represents current supercritical steam cycles with steam conditions of around 3600 psi, 1100F, 1100F and ultra supercritical (USC) steam conditions are on the order of 4000 psi, 1300F, 1300F.

Oxygen combusiton

As fuel is burned in air, which consists of 21% oxygen, 78% nitrogen and 1% other gases, the oxygen chemically combines with the hydrogen and carbon in the fuel releasing heat and forming water and CO_2. The nitrogen is also heated and carries significant energy away in the flue gas. Heat transfer in industrial furnaces used for such processes as melting glass and metals is dominated by radiant heat transfer. Replacing air with oxygen increases radiant heat transfer due to the increased flame temperature and reduces heat loss in the flue gas resulting in an overall improvement in efficiency.[3]

In a process, such as a power boiler where convective heat transfer is equally as important as radiant heat transfer, the reduction in the gas mass flow from pure oxygen firing would have a significant negative impact on the overall boiler heat transfer and efficiency.

Oxy-coal combustion is based on replacing the nitrogen in air with CO_2 creating a synthetic air mixture. Replacing the air to the unit with recycled flue gas significantly increases the CO_2 concentration in the flue gas, facilitating its capture and disposal, while increasing the gas mass flow to that needed for effective convective heat transfer in the unit. The basic Oxy-coal combustion arrangement is shown in Figure 3. The

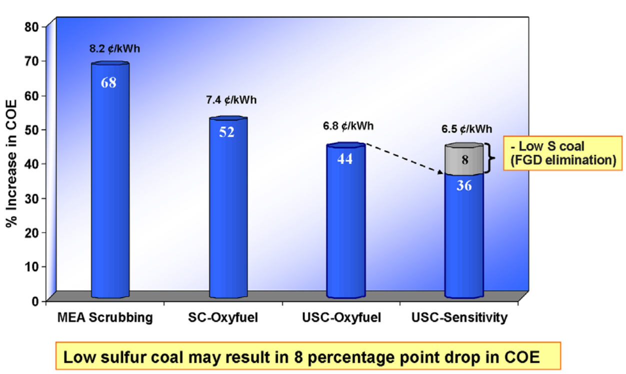

Fig. 1 Impact of CO_2 capture on plant cost relative to air-fired plant (ref. 1).

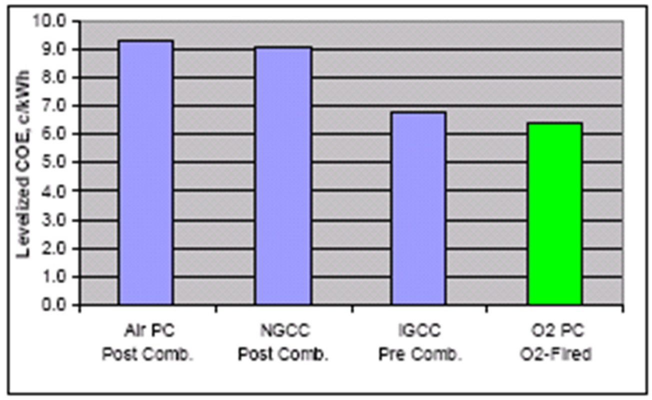

Fig. 2 Comparison of levelized COE among alternative technologies (ref. 2).

Oxy-coal unit is started up using air similar to any other pulverized coal (PC) fired unit. Once at a minimum stable load, the air inlet dampers to the fans are gradually closed which results in recycled flue gas replacing the air. As air is removed, nearly pure oxygen is introduced into the recycled flue gas to maintain safe and optimal combustion conditions in the boiler. This mixture of recycled flue gas plus oxygen is referred to as synthetic air. Figure 4 compares the composition of air to synthetic air. The significant reduction of nitrogen in the synthetic air reduces nitrogen oxides (NO_x). The additional oxygen introduced at each burner to stabilize and complete combustion results in the oxygen content in the synthetic air being slightly lower than normal air.

While the oxygen required for combustion could be satisfied using only pure O_2 injected at the burner, it would not necessarily provide the mass and volumetric flows needed to mix the fuel and oxygen at the burner or to achieve required convective heat transfer in the boiler and air heaters. Use of synthetic air allows the higher mass and volumetric flows to be provided as well as providing the necessary primary air to the pulverizers for transport and drying of the coal.

As part of the recycle process, the lack of nitrogen will naturally concentrate the CO_2 and other constituents. The coal analysis, oxygen purity, air-in leakage, and combustion efficiency will determine the degree of CO_2 concentration that can be achieved in the flue gas, typically about 80% on

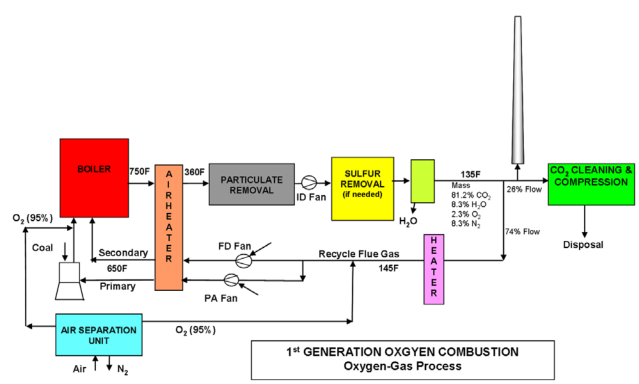

Fig. 3 Typical oxygen combustion process

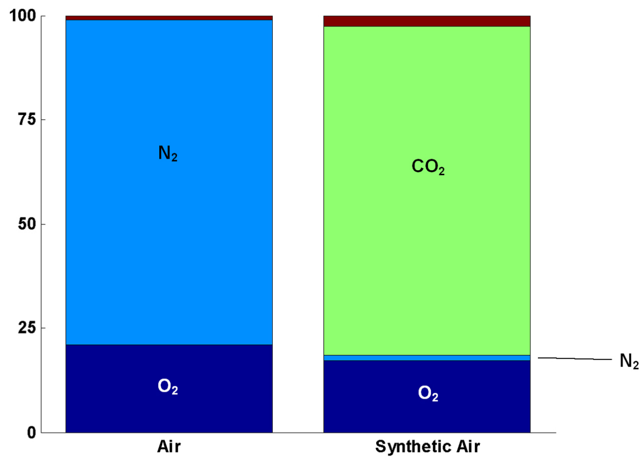

Fig. 4 Synthetic air composition compared to air.

a mass basis. Figure 5 compares the composition of the flue gas with oxygen combustion of coal in synthetic air versus normal air.

Because 65% to 80% of the flue gasses are recycled back to the boiler, the flow extracted from the process for final cleaning and compression prior to disposal is relatively small, 35% to 20% of the flow to the stack for an air-fired unit of the same capacity. The removal of most of the nitrogen from the process also concentrates the other flue gas constituents in the recycle loop by a factor of about 3.5 compared to air firing. As a result, even low sulfur coals will produce flue gas with sulfur dioxide (SO_2) concentrations more typical of medium sulfur coals. For example, a coal with sulfur content of about 1% will produce sulfur concentrations within the boiler and recycle loop equivalent to a coal with about 3.5% sulfur. To prevent excessive corrosion, a scrubber may be needed.

The concentration of NO_x, particulate, Hg, SO_3 and SO_2, the emission limits, and concerns for erosion dictate the design of the air quality control system (AQCS). Water is also concentrated to higher levels than in conventional flue gas and much higher than in air. In addition to the effect of recycle on

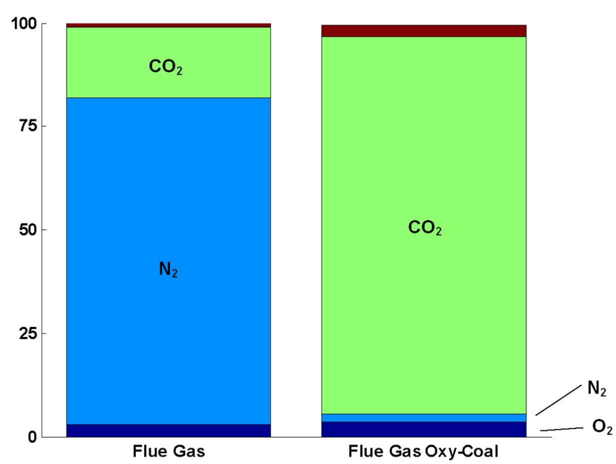

Fig. 5 Flue gas composition with oxygen combustion compared to normal air.

moisture concentration, water added by a flue gas desulfurization (FGD) system significantly increases this concentration. Coal moisture content and combustion considerations dictate the level of moisture removal and reheat necessary to protect the equipment from corrosion and ensure pulverizer and combustion performance. Depending on the circumstances, moisture removal can be located in the full stream or only in the stream to the pulverizers. When using a wet scrubber, the recycle gas will be saturated at whatever final temperature it is cooled to, so it must be slightly reheated before it enters the fans. The degree of final cleaning and compression will vary depending on the means of transportation of the CO_2 stream and the tolerance of the final disposal reservoir. At a minimum, the moisture must be removed to protect the CO_2 compressor.

Although the properties of the flue gas differ from those with air firing due to the lack of nitrogen, studies have shown that by adjusting the design recycle ratio, an existing boiler can be converted to Oxy-coal combustion without changing existing heat transfer surfaces with only a small impact on fuel efficiency. For new units, arrangements can be optimized for reduction in equipment size and improved performance.

Characteristics of oxygen

Every day we experience and use gaseous oxygen at 21% volumetric (dry) concentration in the air. Oxygen itself is a colorless, odorless, tasteless, nonflammable gas. A potential danger is that many substances which do not burn in air may burn in an oxygen-enriched atmosphere (> 23.5% O_2). Liquid oxygen is extremely cold (-297F) and oxygen as a liquid or cold dry gas may cause severe frostbite to the eye or skin.

In addition, higher concentrations of oxygen (25% to 75%) present a risk of inflammation of organic matter in the body. Elevated oxygen levels may result in cough and other pulmonary changes. High concentrations of oxygen, >75% under pressure, cause symptoms of hyperoxia which include cramps, nausea, dizziness, hyperthermia, ambylopia, respiration difficulties, bradycardia, fainting spells, and convulsions.

Oxygen system purge

To maintain clean conditions in the oxygen injection lines into the flue gas oxygen injection/mixing device and to the individual burner oxygen lances, a purge and cleaning system, using either air or low pressure slightly superheated steam, is required for purging and cleaning the oxygen lines prior to admitting oxygen to these lines. As oxygen injection begins, the purge media is gradually removed. A positive flow must be maintained in the oxygen lines at all times.

The oxygen lances to the burners are retractable and no purge is required while air firing or when a burner is out of service. Prior to introducing oxygen into the burner lance, it must be purged to clear debris and cool the lance.

Transitioning from air firing to oxygen firing

The boiler is started up in the usual manner on air firing and brought up to approximately 40% stable load. The oxygen supply system is started and ready for service prior to initiating the flue gas recycle mode. A typical Air Separation Unit (ASU) requires over a day to achieve full oxygen delivery when started up from ambient temperature. Oxygen flow at lower quality is available much sooner and can be used during boiler startup if a rapid start is desired but may extend the time required to reach full load on Oxy-coal combustion. The quality and available flow depend on the specific ASU design.

Once stable pulverized coal operation is achieved, the following procedure is used for the transition to Oxy-coal firing:

1. With the forced draft (FD) and primary air (PA) fan inlet air control and isolation (tight shut-off) dampers fully open at this point, the flue gas recycle flow control damper will be gradually opened initiating flue gas to the FD and PA fan inlet flue.

2. Once the recycle flow control damper is fully open, the FD and PA fan inlet air control dampers are gradually closed increasing the recycle flue gas flow into the FD and PA fan inlet flue. Once the inlet air control dampers are closed, the associated air isolation dampers are closed. If the desired recycle flue gas flow is not achieved when the FD and PA fan inlet air supply dampers are fully closed and the recycle damper is fully open, the stack inlet damper (or damper to the CO_2 compression system) can be gradually closed to force additional flue gas to the FD and PA fan inlet flue. Flue gas flow to the stack must be maintained until the CO_2 compression system is in service. When operating in equilibrium, the flue gas flow to the CO_2 compression system (or stack) is equal to the sum of the excess oxidant (air and/or oxygen) added, any air infiltration, and the products of combustion.

   The boiler is in full flue gas recycle mode once the FD and PA fan inlet air control and isolation dampers have fully closed. Unit load demand controls the recycle demand. Recycle gas flow can be used to trim furnace absorption (separator outlet enthalpy). Increasing recycle decreases absorption and vice-versa.

   The FD and PA flows are measured and temperature compensated based on the densities of the air and oxygen/recycle gas flow streams. This density compensation will have to account for the changing constituents of the gas stream with air and synthetic air as well as during transitions between air and oxygen firing modes.

3. Oxygen is injected into the recycle flue gas stream. Oxygen is also supplied to the lances in the operating burners. The ASU Demand is the difference between theoretical stoichiometric oxygen requirement corresponding to the total Btu input plus the target excess oxygen and the oxygen available from incoming air and recycled flue gas. The ASU Demand is trimmed to maintain the target excess oxygen at the economizer outlet.

   The O_2 flow to the oxygen mixer is controlled to maintain a minimum oxygen concentration by volume in the full recycle stream.

   The total O_2 to the in-service burner lances will be a proportional function of the total oxygen demand on the unit. The O_2 flow to the individual burners associated with a pulverizer will be a function of that individual pulverizer demand compared to the total firing rate demand. Distribution between burners is preset during commissioning using manual valves on each burner lance.

   During the transition from air to oxygen firing, oxygen flow initially goes to the oxygen lances on the in-service burners. As the flow of air flow is reduced, the oxygen concentration after the oxygen mixer is decreasing. When it reaches a minimum limit, oxygen flow to the mixer will be controlled to maintain the desired oxygen concentration at this limit. Burner lighters will be kept in service throughout the transition to assist in maintaining burner stability. The total oxygen demand is trimmed to maintain the Target Excess Oxygen leaving the boiler. The local concentration of oxygen in the recycle flue gas downstream of the oxygen mixer must remain below maximum oxygen concentration limit under all circumstances. The demand for Total Oxygen is coordinated between the boiler and the oxygen supply system. The boiler control system provides a feed-forward signal of the total oxygen demand to the ASU oxygen supply control system.

4. Starting an additional pulverizer under oxygen combustion is similar to under normal air firing. The first step is to change the synthetic air flow on the burners associated with the pulverizer to be placed in service from cooling to light-off flow. The igniters are then placed in service on these burners. Oxygen flow demand for the other in-service burners is temporally increased to help maintain flame stability and decrease the risk of high O_2 concentration in the recycle flow as oxygen is added. PA flow through the pulverizer is established when its burner line shutoff valves are opened, increasing the recycle flue gas flow required. This increase will result in a temporary decrease in flow to the CO_2 compression system which is responsible for backpressure control equivalent to that which would otherwise be provided by the stack.

   The oxygen lances for the burners coming into service must be purged just prior to admitting fuel to ensure they are clear of debris and sufficiently cool to permit introduction of oxygen. After the pulverizer and feeder are started, oxygen flow to the burner lances is initiated. This will automatically back the other pulverizers down to maintain heat input and redistribute the oxygen to the in-service burners based on pulverizer load. As stable conditions are achieved at the new total heat input, oxygen to the burners is returned to its normal set point.

5. Recycle flue gas and oxygen flow demands will follow changes in boiler heat release demands similar to normal air-fired systems. Oxygen flow to the burner lances is temporarily increased during faster load changes in either direction until steady state load conditions are achieved. Flue gas and oxygen flows lead fuel flow on load increases. The process is opposite for a load decrease with fuel flow leading recycle flue gas and oxygen flows.

Transitioning from oxygen firing to air firing

The boiler load is reduced to the selected transition load, flow through the stack is re-established, and the CO_2 compression system is removed from service. The oxygen shut off valves to the burner injection headers are closed as each pulverizer is shut down. Flue gas recycle is reduced by:

1. Gradually opening both the FD and PA fan inlet isolation (tight shut-off) dampers until fully open while keeping the flow control dampers fully closed.

   Both the FD and PA fan inlet air control dampers and the stack inlet damper will be gradually opened. As air displaces the flue gas, the oxygen demand decreases reducing the injection rate to the in-service burners and oxygen mixer.

2. As the oxygen injection rates are reduced based on the total oxygen demand, the oxygen supply system output will be reduced and excess oxygen will be vented as necessary when the boiler demand is less than the output of the ASU.

3. Once the FD and PA fan inlet air dampers and the stack inlet damper are fully open, the flue gas recycle damper will be gradually closed and the unit is in air-fired mode.

4. When the oxygen is no longer being demanded, the shut-off valves for the oxygen mixer and to the burners are closed.

Oxygen combustion and CO_2 sequestration experience

Oxygen combustion and CO_2 sequestration activities date to the late 1970s when the oil embargo raised interest in enhanced oil recovery (EOR) where CO_2 is injected to enhance recovery of oil from existing wells. These activities produced what can be considered the first generation of plant designs to provide concentrated CO_2 using oxygen combustion.

When global warming concerns put the spotlight on the CO_2 emissions from power generation in the late 1990s, interest in this technology was revitalized, especially in Canada through the CANMET's CO_2 Consortium since Canada at that time was approaching carbon management more aggressively than the U.S. The Canadian Clean Power Coalition and more recently the U.S. Department of Energy have sponsored a number of programs addressing all three of the CO_2 capture technologies as well as studies on carbon sequestration.

In 2001, B&W and Air Liquide began Oxy-coal combustion R&D efforts on the element with the greatest impact on the process cost and performance, the oxygen system. Additionally, Oxy-coal combustion tests were performed at 5MBtu/h scale in B&W's Small Boiler Simulator (SBS) facility on both Illinois #6 and Powder River Basin (PRB) coals.[4]

The results of this pilot scale testing showed that with stable flame and optimized oxygen and recycle flue gas, almost 85% CO_2 concentration and a 65% NO_x reduction could be achieved. This NO_x reduction is not only due to the lack of nitrogen in the system but also to a re-burn effect and relatively low air infiltration. Unburned combustibles were lower than with air firing while furnace exit gas temperature, convection pass heat absorption, and boiler exit gas temperature were similar to air firing. There were no negative impacts on boiler operation. In fact, the system could be easily started up, load changed, and shut down, and operational behavior and steam side performance were nearly the same as for a conventional air-fired unit.

This success of the pilot scale testing has led to the pursuit of a reasonably sized demonstration in a power plant environment.

Large scale testing

The largest test facility in the world that has operated under Oxy-combustion conditions with pulverized coal to date is B&W's 5 MBtu/h (1.5 MW_t) SBS facility. Other test facilities being proposed include the 30 MW_t Vattenfall project in Germany and the 30 MW_e Callide project in Australia. During 2005, the design and costs for a 25 MW_e demonstration program on a unit at the City of Hamilton, Ohio, were developed, but funding for the actual demonstration could not be arranged. With the need to support design of commercial scale projects, B&W and Air Liquide decided in late 2006 to convert B&W's existing 30 MW_t Clean Environment Development Facility (CEDF) in Alliance, Ohio, to an Oxy-combustion system.

The CEDF was built with funding from B&W, the U.S. DOE and the Ohio Coal Development Office and was started up in 1993. It was designed as a combustion test facility with provisions for performing emissions control and air toxics testing. The furnace and convection pass are designed to provide a time-temperature characteristic equivalent to a large utility boiler. It incorporated an EL-56 pulverizer for coal preparation and an indirect coal feed system, full flow dry scrubber, fabric filter, and electrostatic precipitator (ESP). Over the years it has been used in support of the U.S. DOE's Combustion 2000 program, the "Advanced Emissions Control Development Program" as well as early mercury testing and has produced excellent data in support of three generations of pulverized coal burners and variations for specific applications.[5] In 2005, in cooperation with Air Liquide, it was also used to test partial Oxy-firing.

To permit full Oxy-firing, additional flues, an oxygen supply, oxygen mixers, a full flow wet scrubber, additional coal preparation equipment, and controls and instrumentation have been added. In addition, the combustion system was converted to allow direct firing to permit full Oxy-combustion operation with lignite. The testing will address the impact of both Oxy-firing and the various coals on coal preparation, ESP and wet scrubber performance and operation with the different flue gas composition; evaluate transitioning between air and oxygen firing, load changes and major system trips including Master Fuel Trip; and support nearly full-scale testing of a new Oxy-burner for lignite. In addition to testing with Saskatchewan lignite, it will be operated with eastern bituminous and sub-bituminous coals.

SaskPower project

During the next 20 to 30 years, SaskPower will be making major decisions concerning the refurbishment or replacement of virtually its entire fleet. Saskatchewan's 300 year supply of readily accessible lignite coal remains their most cost-efficient and stable-priced fuel for base load generation but there are environmental concerns.

For several years SaskPower has been involved in evaluation of technologies for carbon dioxide management in coal fired power plants. Recently they announced a Clean Coal Project that will capture over 90% of the carbon dioxide produced from coal combustion.[6] This project will result in a power plant providing 300 net megawatts (MW) of electricity while capturing about 8,000 tonnes of CO_2 a day for enhanced oil recovery to extract millions of new barrels of oil from Saskatchewan oilfields. Additional emissions-control technologies to be incorporated will result in a unit with near zero emission status.

SaskPower thoroughly examined and researched both Oxy-coal and the post-combustion clean-up processes. Based on the current state of both technologies, and project-specific parameters, they selected Oxy-coal and expect it to provide the best environmental performance and lowest cost.

After selection of Oxy-coal, SaskPower came to an agreement with Babcock & Wilcox Canada (B&W) and Air Liquide in late 2006 to jointly develop the Oxy-coal technology as the core process for a new 300 MW net unit to be located at their Shand facility near Estevan. Marubeni Canada and Hitachi will supply the turbine generator set, B&W will supply a pulverized coal-fired supercritical once through boiler and Air Liquide will provide the air separation plant and CO_2 compression system. The Oxy-coal technology nearly eliminates emissions of combustion byproducts, including greenhouse gas emissions, and may be the worlds first near zero emissions pulverized coal unit.

Significant design work and costing is currently underway to assess whether SaskPower should proceed to the construction phase. When the decision is made to proceed, this power plant will be the first of its kind in a utility scale application. The decision on whether to proceed will be made in mid-2007 for an in-service date of 2011.

Conclusions

Oxy-coal combustion offers a means of continuing to utilize the abundant reserves of coal in the generation of electricity while achieving a near zero emissions unit. The reduction in CO_2 emissions assumes the captured CO_2 can be safely sequestered. Oxy-coal combustion technology is applicable to existing coal-fired units and not just new units. Even with the high impact on net plant MWs from the oxygen supply system and CO_2 compression train, studies show that Oxy-coal combustion is competitive with other the CO_2 capture technologies currently being proposed.

One of the major problems from a control standpoint will be remembering that the O_2 flow through the unit is now independent of the total gas mass flow through the unit. Also, flow measurements will have to compensate for the varying densities as the compositions of the air and gas flow streams change during unit operation. Operation with oxygen combustion and CO_2 sequestration will require greatly increased dependence on oxygen measurement and control than has been required with air firing.

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Key Words

Pulverized coal
Oxygen combustion
Oxy-coal
CO_2 capture
Sequestration