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Alstom's Oxy-Firing Technology Development And Demonstration - Near Term CO_2 Solutions

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ABSTRACT

This paper provides an update of Alstom's development of oxy-combustion technology for carbon capture and storage (CCS) from fossil fuel fired power plants. Developments efforts have now reached large pilot testing stages and are providing a strong foundation for large-scale demonstration plants, the last step before commercial plants.

Alstom is engaged in development of oxy-technology for both pulverized coal and circulating fluid bed applications. The CFB oxy-boiler concept has been validated during a series of 3 MW_{th} pilot test campaigns and positively evaluated during several engineering and economic studies. Oxy pulverized coal firing has also been favorably assessed in laboratory and technical-economic studies. The first complete oxy-fired plant with CO_2 capture, Vattenfall's 30 MW_{th} Schwarze Pumpe oxy-combustion plant has been constructed and successfully operating since September 2008. Alstom supplied the oxy-boiler for this plant and is a partner in the two-year testing program. Additionally, a comprehensive test program focusing on tangentially-fired boiler development is being conducted in parallel, which includes 15 MW_{th} tangentially fired testing in

Alstom's Boiler Simulation Facility. Testing is evaluating oxy-combustion design options including gas recycle configurations and oxygen injection schemes. Project partners include the US DOE, the Illinois Clean Coal Institute, and ten (10) electric utility companies.

Considerable information and understanding is being gained from these pilot efforts as well as from complementary small scale tests and engineering design studies, which positions Alstom to be ready for the next step of large (100-350 MW_e) oxy-fired CCS demonstration plants.

BACKGROUND

Since fossil fuels will remain the primary energy source for power generation for the foreseeable future, coal-fired power plants will likely need to incorporate systems that enable the cost effective capture and sequestration of their CO_2 emissions. One of the promising near-term technologies to accomplish this is oxy-combustion.

The basic concept (see Figure 1) of oxygen firing with today's coal combustion technologies is to replace combustion air with a mixture of oxygen and recycled flue gas. The resulting flue gas comprises primarily CO_2 and H_2O vapor along with some N_2, O_2, and trace gases like SO_2 and NO_x. Consequently, the flue gas can be processed relatively easily (through rectification or distillation) to enrich the CO_2 content in the product gas to more than 99% purity for use in enhanced oil or gas recovery (EOR or EGR). Alternatively, the flue gas can be more simply dried and compressed for geological storage, which results in near-zero gaseous emissions from the power plant.

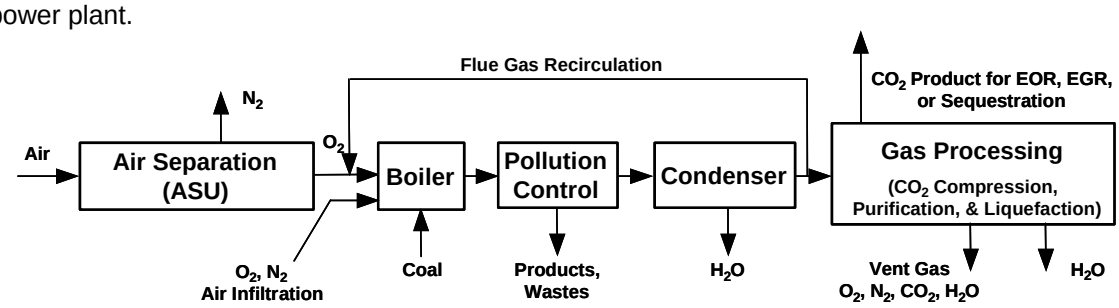

Figure 1 - Simplified Oxy Combustion Process Concept

The primary impacts of oxygen firing on the boiler concept and design is associated with the reduced combustion gas flow due to the removal of nitrogen present with air firing and the differences in the thermal and radiative properties of the gas comprised of mostly CO_2. Recycling a portion of flue gas compensates for these impacts. Thus, the furnace temperature can be maintained low enough to avoid ash slagging, fouling and corrosion, and the heat flux to furnace walls within the limits imposed to prevent overheating. The CFB technology offers an additional freedom in controlling thermal conditions with an external fluidized bed heat exchanger that can replace some or, in theory, all of the flue gas recycle (FGR) needed to compensate for the removal of nitrogen.

Oxy-combustion technology can be used for new plants or applied (retrofit) to the large fleet of existing PC and CFB power plants. Economic evaluations show that purifying the flue gas from oxygen-fired systems is competitive with post-combustion CO_2 capture technologies or with IGCC-based technologies. Oxy-combustion CCS costs are estimated to be significantly less than that of current commercial amine technologies. [1,2]

Oxy combustion technology utilizes commercially available equipment, which can be scaled and optimized for this application, allowing less time for commercial deployment. It is noted that all CCS CO_2-capture technologies will also require development of CO_2 pipelines and storage or sequestration capability, in complement. A development timeline based upon Alstom's technology roadmap is shown in Figure 2.[3]

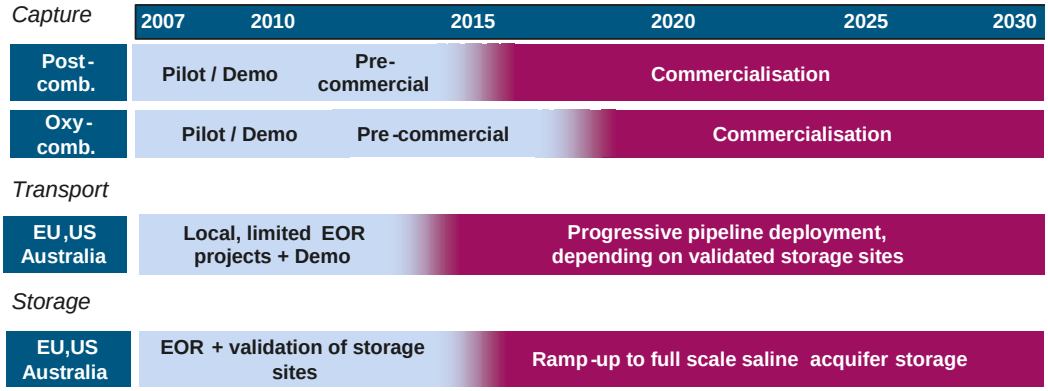

Figure 2 – Alstom Technology Roadmap

Alstom has been actively evaluating the technical and economic viability of CCS technologies for more than a decade and is focusing on development of post-combustion scrubbing and oxy-combustion, as these are applicable to both new and existing power plants. Small demonstrations are currently underway, which will be followed by pre-commercial large demonstration projects. A set of different capture options is projected to be fully commercially available by 2020. Post-combustion technologies such as advanced amine or ammonia scrubbing will be commercially available as early as 2014-15 based upon the fact that they can be tested at a smaller scale and flexibly deployed in several trains at a larger power plant. Oxy-combustion will be commercially available one to two years later, considering the status of our current large pilot projects and the fact that a number of large-scale demonstrations are currently being planned.

OXY-CFB DEVELOPMENT

Oxy-combustion requires tempering of the combustion process to control the furnace temperatures. In oxygen-fired PC boiler designs this is accomplished by recycling a portion of the cooled flue gas. In an oxygen-fired CFB boiler, the temperature control can also be achieved by recirculating cooled solids to the furnace through a fluid bed heat exchanger. This characteristic allows the CFB boiler to be made smaller and less expensive than the equivalent air fired CFB boiler in a new unit application. For dual oxy- and air-fired operation or for retrofit applications, the CFB boiler would retain similar size as the air-fired design.

The potential reduction in size of an oxy-fired CFB is illustrated in Figure 3, which compares an oxy-design operating with a 70% oxygen concentration (relatively low level of gas recycle) with an air-fired design.[4] Oxy-fired CFB designs for oxidant concentrations between 40% and 50% oxygen have also been studied. The reduction in size of the oxy-fired design results in cost savings for the boiler and downstream equipment, which helps to offset some of the additional costs for the air separation unit that provide oxygen and the gas purification and compression system.

Initially, commercial oxy-CFB designs will likely have dual capability to operate in either oxy- or air-fired modes providing a higher degree of flexibility and reduced risk. Optimization of oxygen concentration (gas recycle rate) will likely depend upon consumer and site-specific factors as well as material costs and development progress.

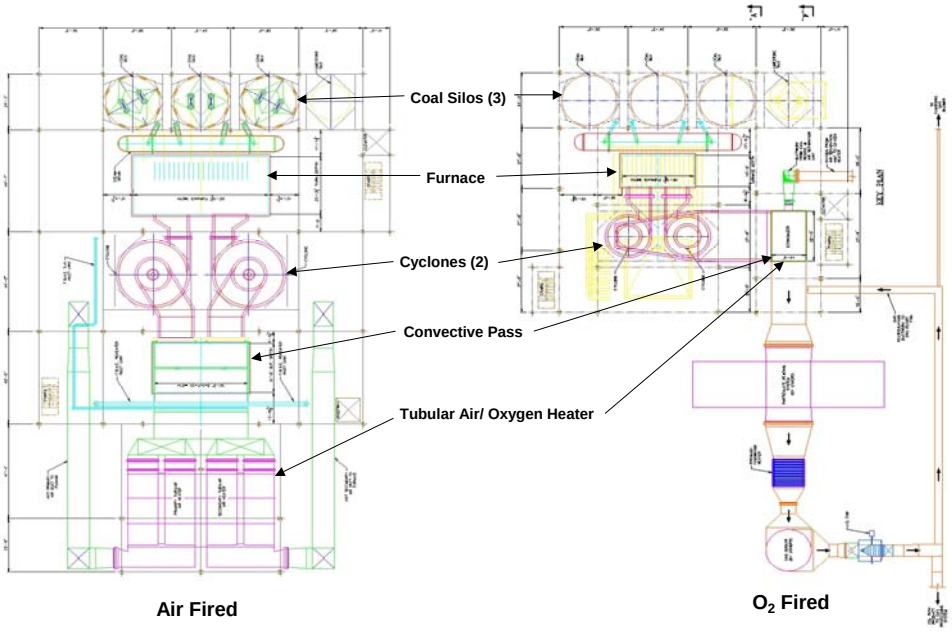

Figure 3 – Plan Views of Air Fired CFB and Oxy-Fired (70% O_2) CFB

The oxygen-fired CFB concept has been validated in Alstom's bench-scale and pilot-scale (3 MW_{th}) test facilities and has been discussed in greater detail previously.[4,5,6] More than 300 hours of pilot testing has been performed, which addressed oxygen concentrations up to 70%. Some of the key results included:

- Operation - No agglomeration issues of bed solids even with local oxygen concentrations up to 70% by volume. Some recarbonation (i.e., reverse calcination) occurred, where the temperature dropped below the calcination temperature, as expected.
- Heat Transfer - In-furnace heat transfer coefficients for oxy-firing were comparable to air-firing (dominated by solids effects). The convection pass heat transfer coefficients were higher with oxygen firing than with air firing, as expected.
- Emissions – Lower NOx emissions were experienced with oxygen firing than with air firing, due to absence of nitrogen from air. The CO emissions increased somewhat with oxygen firing, due to high CO_2 partial pressure in the flue gas. The carbon in ash with O_2 firing was comparable to carbon in ash with air firing. Emissions of N_2O were low under all circumstances. Similarly, the emissions of mercury, VOC, and other trace metals with oxy-firing were at least as low as with air firing.
- Sulfur Capture - Sulfur capture with lime only in the downstream baghouse/FDA dry scrubbing system was about the same with oxygen firing as compared to air firing.

These and other results show that oxy-CFB technology can be easily developed from conventional CFB boilers, so that a medium (100-350 MW_e) scale oxy-fired CFB demonstration plant could be developed on short term, followed on medium term by larger scale commercial plant at relatively low risk. The design is based on proven, reliable, commercially available boiler technology.

A power generation technology with CO_2 capture based on oxy-CFB will take direct benefit from operating flexibility and from the wide range in fuel experience with Alstom CFB boilers. The ability to fire low-cost fuels or co-firing wastes allows less dependence on expensive high rank imported coal, and thus, reduces the Cost of Electricity. Furthermore, the capability of co-firing biomass may allow additional CO_2 credits.

OXY- PULVERIZED COAL DEVELOPMENT

Alstom has been and is currently actively involved in several small-scale and pilot oxy test programs including European research programs ENCAP (Enhanced Capture of CO_2) and OxyBurner and in the German research program ADECOS (Advance Development of the Coal-Fired Oxyfuel Process with CO_2 Separation), several research institutes are focusing on oxy-fuel laboratory and pilot scale testing. Large pilot test programs currently underway include:

- A 30 MW_{th} oxy-firing pilot plant by Vattenfall at their Schwarze Pumpe station in Spremberg, Germany. Alstom designed and built the oxy-combustion boiler and electrostatic participator and is a partner with Vattenfall conducting a comprehensive two-year test program. This plant is the first complete oxy-combustion plant, which includes the integrated system from the air separation unit to the gas purification and compression systems. The CO_2 will be compressed and liquefied for storage experiments to be conducted.
- A 32 MW_{th} oxy-firing demonstration project developed by Total, for which Alstom is retrofitting an existing boiler to natural gas oxy-combustion. The Total project is likely to be the first integrated capture, transport and storage unit in Europe. The captured CO_2 will be transported over a 30 km pipe and stored in a depleted gas field in Lacq, South of France.
- A comprehensive tangentially-fired boiler development test program utilizing Alstom's 15 MW_{th} tangentially-fired Boiler Simulation Facility (BSF) and 15 MW_{th} Industrial Scale Test Facility (ISBF) in Windsor, CT, USA. Testing is being conducted to assess a broad range of oxy-combustion design options, which requires flexibility that is typically beyond the capabilities of operating plants. Project partners include the US DOE, the Illinois Clean Coal Institute, and ten (10) electric utility companies.

Vattenfall 30 MW_{th} Oxy Pilot Plant at Schwarze Pumpe

The Vattenfall 30 MW_{th} oxy-pilot plant is one of the key milestones on the way towards a commercial scale power plant based on the oxyfuel technology. The entire process chain for the oxy-combustion system at an industrially relevant size is installed at Vattenfall's Schwarze Pumpe station, approximately 150 km southeast of Berlin in Germany. (See Figures 4 and 5.) Alstom has supplied the boiler and additional flue gas cleaning equipment for this plant, which has been in operation since September 2008. The project has already proven the feasibility of the oxy-combustion concept, and is now being further optimized and parametrically tested both in air-firing and in oxy-firing modes.

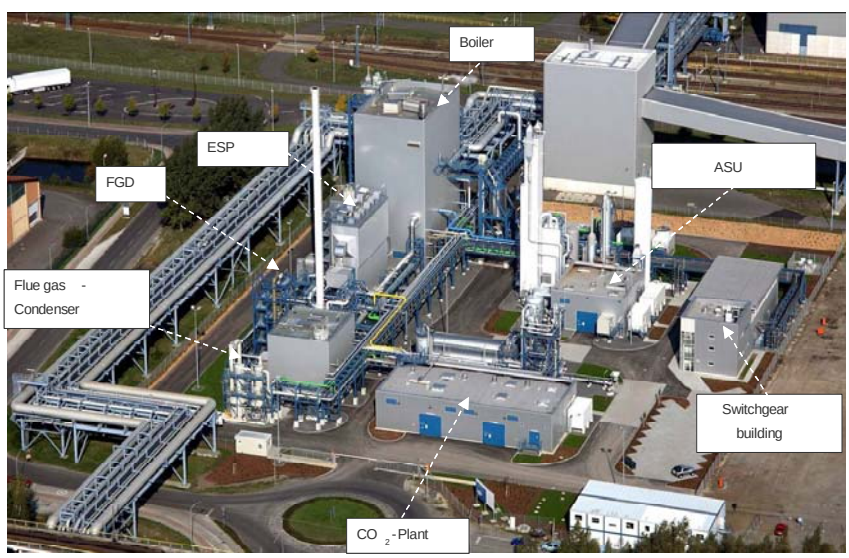

Figure 4 – Vattenfall 30 MW_{th} Oxy Pilot Plant at Schwarze Pumpe

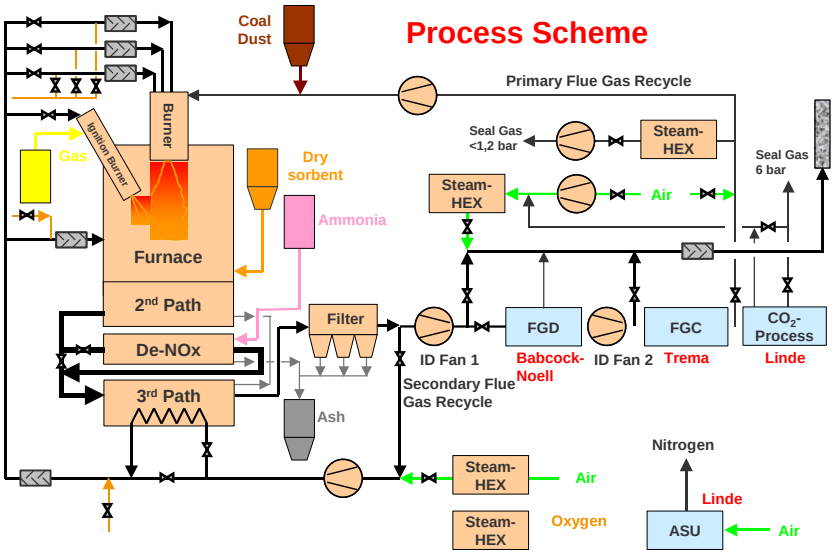

Figure 5 - Vattenfall 30 MW_{th} Oxy Process Flow Diagram

The steam generator is designed as a natural circulation boiler with several gas passes. The furnace is fired from a top-mounted 30 MW_{th} burner; the 2nd and 3rd gas passes containing heat exchanging surfaces with the superheaters and economizers. The burner uses an indirect firing system, and has the flexibility to operate with different fuel types, various oxidant flow rates and oxygen injection methods. Several options for mixing oxygen into the combustion system are possible. In the pre-mixed mode all the oxygen is mixed with the flue gas at one location, while in other modes each single oxidant stream entering the burner or the furnace can have its individual O_2 concentration. Further and more detailed technical descriptions about Vattenfall's 30 MW_{th} oxyfuel pilot plant have been provided.[7,8,9]

The oxyfuel pilot plant is burning dried lignite. More than 1600 hours of operation have been logged through the end of February 2009, with approximately 900 hrs in the oxy-combustion mode of operation. The specified boiler emission limits can be easily achieved in both air- and oxy-firing modes

Pictures of flames from both air- and oxy-firing are shown in Figure 6 firing dried lignite. This oxy-flame was during a pre-mixed oxygen operation mode. Flames comparable with air firing in terms of ignition, flame stability and flame shape have been achieved in the oxy-firing mode.

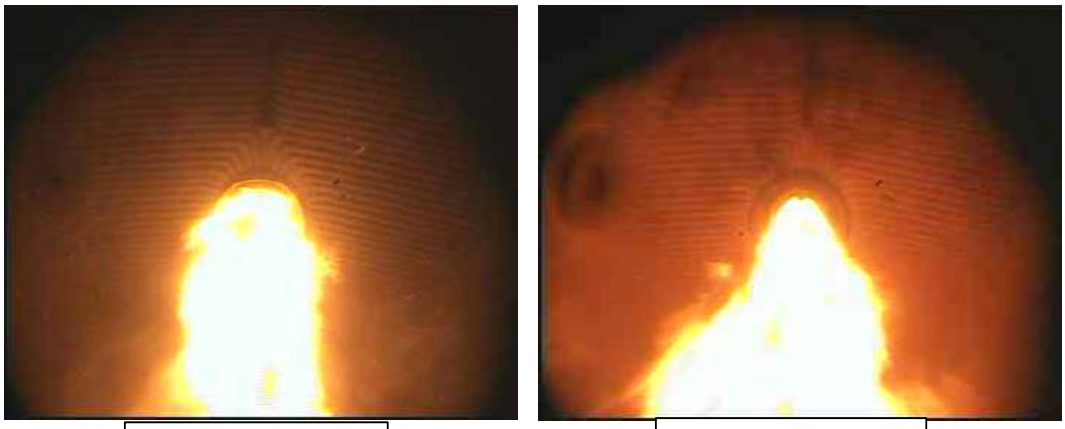

Figure 6 – Photos of Vattenfall 30 MW_{th} Oxy Pilot Burner

Figure 7 shows a graph taken from the process control system demonstrating the rapid switch from air firing mode to oxy-firing mode and gives an idea about the required time for changing the operation mode. In addition, the enrichment of CO_2 in the flue gas is shown with a resulting CO_2 concentration of more than 85% vol. dry basis in the oxy-firing mode. The coupling and operation of the ASU and the CO_2 gas processing unit with the steam generator and the subsequent flue gas cleaning equipment are performing quite well.

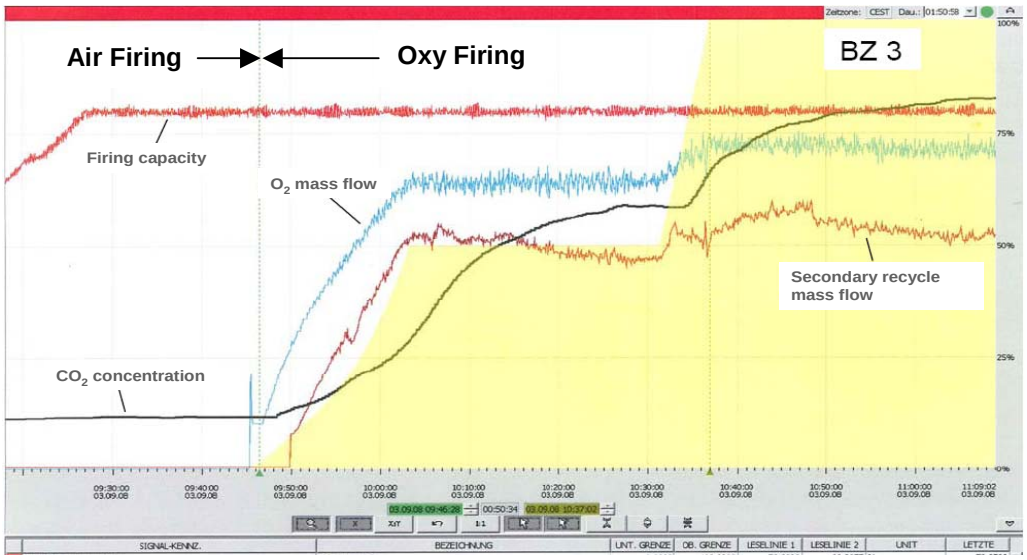

Figure 7 - Operating Graph During Switch From Air to Oxy-Firing

Valuable knowledge has already been gained during the design phase, the erection and the commissioning of the steam generator with respect to the oxy-combustion technology. Detailed data on performance, operational and design requirements is being obtained as the two-year test program is carried out.

<u>Tangentially-Fired Boiler Development Test Program</u>

In October 2008, Alstom began a two-year program to conduct 15 MW_{th} pilot test work focusing on development of an oxy-combustion system for tangentially-fired PC boilers. This effort is complementary to the Vattenfall 30 MW_{th} pilot plant program discussed above. Major program objectives include:

1) Design and develop an innovative oxy-combustion system for existing T-fired boiler units that minimizes overall capital investment and operating costs
2) Evaluate performance of oxy tangentially-fired boiler systems in pilot scale tests at Alstom's 15 MW_{th} Tangentially-Fired BSF and 15 MW_{th} ISBF
3) Address optimization steps for design of oxy commercial utility boilers by focused testing in the BSF and ISBF and improvement of engineering and CFD tools.

This program is evaluating several oxy-combustion system design concepts including various flue gas recirculation scenarios and oxygen injection options using engineering and 3-D computational fluid dynamics (CFD) modeling tools. The most promising designs will be evaluated during 15 MW_{th} oxy-pilot testing.

Screening Evaluations

Several oxy-firing scenarios are being evaluated through techno-economic analysis. A typical 800 MW_e supercritical tangential-fired boiler design has been selected and used for the base design and configuration. Alstom's proprietary boiler design codes, updated for oxy-combustion

applications, are being used to calculate overall mass and energy balances, boiler design impacts, and major equipment component sizing requirements for the selected oxy-process scenarios. These include different FGR take-off locations, FGR flow rates and injection locations as well as different oxygen injection schemes. Figure 8 illustrates some of the options for gas recycle and oxygen injection location.

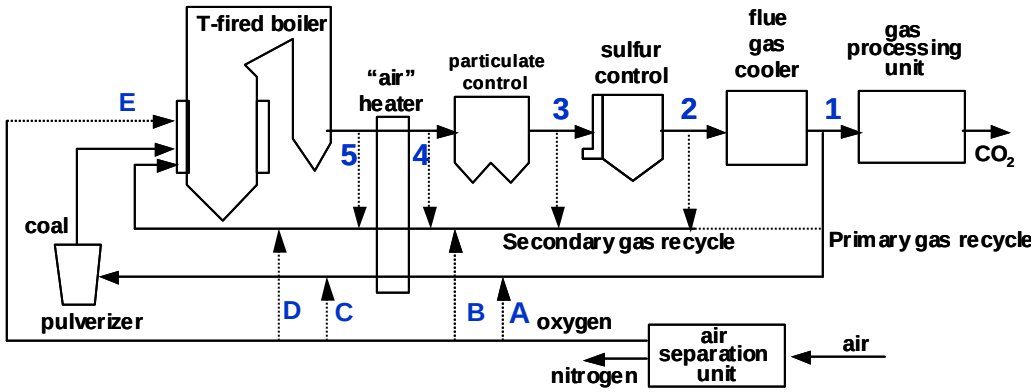

Figure 8 – Simplified Oxy Process Diagram

As gas recycle is taken closer to the boiler outlet, more of the downstream equipment can be reduced in size and cost. However, as gas recycle is taken closer to the boiler outlet, the concentration of impurities returned to the boiler is greater, which impacts ash deposition, corrosion and pollutants, and must be addressed in the boiler design. Trade-offs between boiler impacts and downstream equipment savings are generally controlled by fuel characteristics and site-specific factors.

More detailed evaluation of oxy-firing system design variables and their impacts on boiler performance is being conducted using CFD analysis. Alstom has been applying CFD modeling for oxy-combustion assessments in several programs and has several on-going projects to improve predictive capabilities. Alstom uses the ANSYS/FLUENT™ code, which requires particular adaptation to several aspects for oxy-combustion application including gas and particle radiation properties, gas phase chemistry, heterogeneous char oxidation and gasification reactions, as well as sulfur chemistry.

CFD models, with updated submodels for oxy-firing, were generated to represent the BSF with a detailed treatment of the individual air compartments and coal injection nozzles. These models were calibrated using a series of previous air-fired test data from the BSF. Several sets of simulations are being run to assess impacts of gas recycle rates, oxygen enrichment and oxygen distribution. The simulations are primarily being evaluated for gas temperature distributions, heat flux distributions and combustion performance impacts. An example is provided in Figure 9, which shows the gas temperature distribution for two oxy-combustion cases. The simulations show a shift in temperatures and heat release profile between these cases as the oxygen flow and concentration is changed to windbox compartments and separated "overfire air" locations.

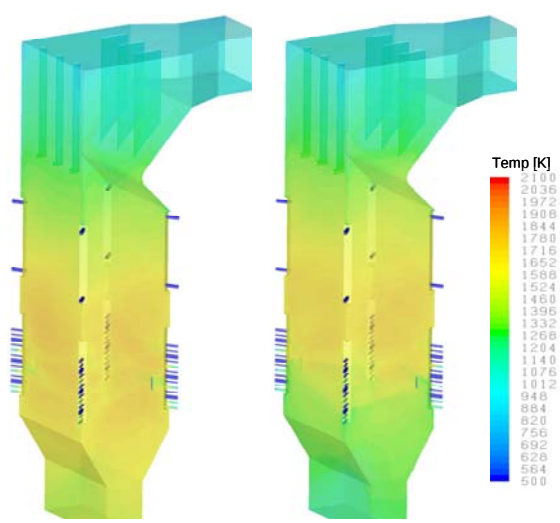

Figure 9 –BSF Oxy Simulations

In addition to the BSF simulations, an 800 MW_e utility boiler is being modeled to compare and confirm the behavior predicted for the BSF. These simulations provide input to the test matrix design for the 15 MW_{th} tangentially-fired testing in the BSF. Predictions from both the engineering performance tools and CFD models will be evaluated during subsequence project tasks as experimental oxy-combustion test data is produced during the 15 MW_{th} testing. Detailed furnace mapping data is specifically being performed to allow refinement and validation of these tools.

15 MW_{th} Test Program

The pilot test program utilizes Alstom's 15 MW_{th} BSF at its Boiler Laboratories in Windsor, CT, USA to generate detailed performance test data under representative tangential firing conditions. Additional tests will be conducted in Alstom's 15 MW_{th} ISBF on a single fuel/air assembly to further assess hardware design, material requirements and flame scanner performance. These facilities have a long successful history of supporting development and commercialization of Alstom's firing systems and other combustion technologies. More detailed descriptions of these facilities have been presented.[10]

Figure 10 – BSF and Tangential Firing System

Figure 10 shows a photo of the BSF and an illustration of tangentially-fired operation. Tangential firing utilizes air / fuel admission assemblies located at the corners of the boiler furnace, which generate a rotating fireball that fills most of the furnace cross section. Fuel / air mixing is limited until streams are joined together in the furnace cavity. This is unlike wall-firing where most of the mixing and flame stabilization occurs at the exit of the burner. Both near-field and global aerodynamics are essential to tangential firing and dictate combustion performance, heat transfer distribution and pollutant formation. These parameters vary between air-firing and oxy-firing modes, which necessitate study and optimization. Due to its scale and design, the BSF provides an excellent experimental tool to replicate tangential firing conditions in utility boilers and isolate variables to study behavior.

BSF tests will cover a range of oxy-combustion scenarios and include a number of coal types. The coals planned for testing include PRB subbituminous, low sulfur Eastern bituminous, Illinois high sulfur bituminous, and lignite. Four (4) BSF test campaigns are scheduled, with each campaign including up to 200 hrs of around-the-clock operation.

Key measurements to be taken during the BSF test campaigns include:

- Operating Conditions- Online Data Acquisition System (Flows, Temperatures, Pressures)
- Heat Transfer – Test Panels, Heat Flux Meters, Heat Flux Probe Measurements
- Gas Composition At Various Locations (CO_2, O_2, H_2O, NOx, SO_2, Total Hydrocarbons)
- Furnace and Convection Pass Gas Temperature Distributions – Suction Pyrometer
- Mercury, Trace Metals, and SO_3 Measurements at Selected Stable Conditions

- Deposition and Corrosion Probes - Analyze the Probes and Collect Deposits for Further Evaluation
- Detailed Furnace Mapping – Temperature, Gas Composition, Particulate Sampling

Currently test preparations are underway including facility modifications required to execute the oxy-combustion testing. Facility equipment additions include:

- Oxygen supply and injection system
- Reconfiguration of gas recirculation systems
- New fabric filter for particulate removal and integrated dry SO_2 scrubber
- Additional instrumentation and controls.

The BSF modifications provide the flexibility to test in six (6) different operating scenarios; baseline air-firing mode and five oxy-fired gas recycle configurations. The facility layout with new equipment is illustrated in Figure 11.

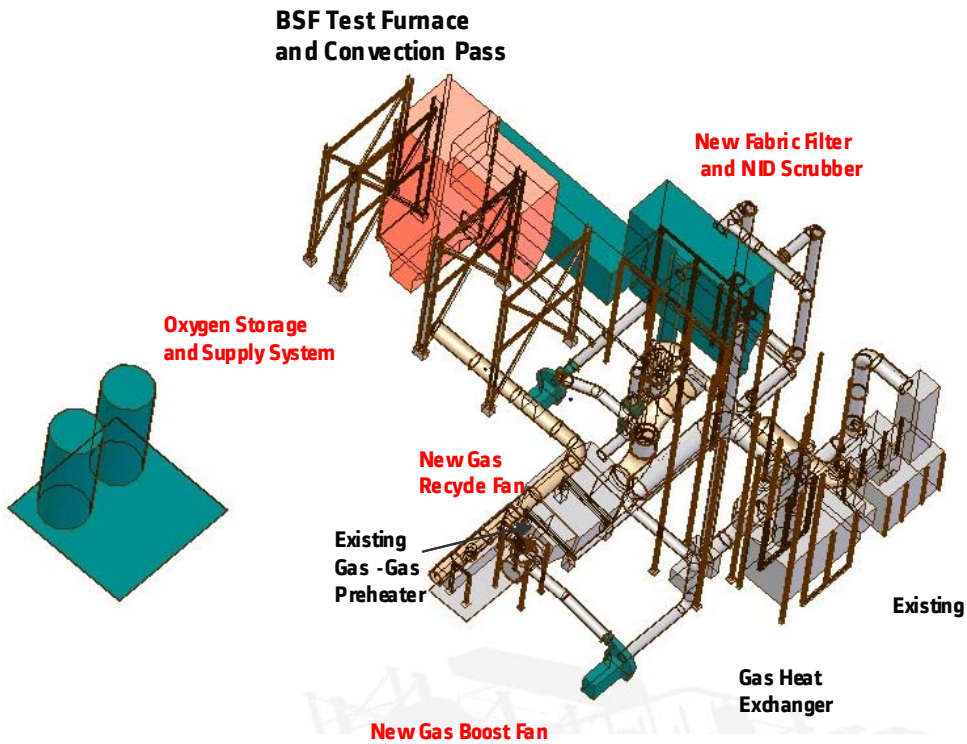

Figure 11 - 15 MW_{th} BSF Equipment Layout For Oxy-Firing

Facility modifications and shakedown are scheduled to be completed in June. The first BSF test campaign is scheduled to begin in July 2009. This campaign will test a broad range of oxy design options and will focus on establishing the basic oxy-design for further optimization. Subsequent campaigns will focus on optimization and fuel specific performance impacts. All of the pilot test work is scheduled to be completed by May 2010. Evaluation of test results, tool and modeling refinement and validation, and reporting are planned to continue through September 2010.

Results of this program, along with complementary results from the Vattenfall 30 MW_{th} pilot and other on-going programs, provide the detailed technical data and engineering tools to confidently proceed with design, construction and a validation of large (100-350 MW_e) oxy tangentially-fired boilers.

CONCLUSIONS

In order to achieve targeted reductions in CO_2 emissions of the power sector, carbon capture and storage or sequestration is necessary. Oxy-combustion is one of the most promising near-term technologies enabling CCS because it is based on proven, reliable, commercially available technologies that reduce risk and allowing near-term (2015-2016) commercialization.

Oxy-combustion technology concepts have been developed and validated at pilot scale for both pulverized coal and CFB applications. The first large (30 MW_{th}) oxy pilot plant has been successful and is a key milestone on the path toward CCS commercialization. Complementary large (15 MW_{th}) oxy tangentially-fired pilot testing is underway to develop technical data and tools for oxy tangentially-fired pulverized coal boilers. These pilot efforts and supporting smaller scale tests and engineering design studies, provide the understanding and knowledge for Alstom to confidently proceed to the next step of large (100-350 MW_e) oxy-fired CCS demonstration plants.

ACKNOWLEDGEMENTS

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