Ultra-Supercritical CFB Technology to Meet the Challenge of Climate Change

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Abstract

Concern about air emissions and the effect on global warming is one of the key factors for developing and implementing new advanced energy production solutions today. One state-of-the-art solution is circulating fluidized bed (CFB) combustion technology combined with a high efficiency once-through water-steam cycle. Development work is under way to offer CFB technology up to 800 MWe capacities with ultra-supercritical steam parameters. Simultaneously, the technology to provide capability for air and oxy-combustion flexible operation to allow carbon capture is being developed.

The proven high-efficiency circulating fluidized-bed (CFB) technology offers a good solution for CO_2 reduction for both repowering of existing coal-fired power plants and in greenfield power plants. CFB technology has excellent fuel flexibility and offers the opportunity to further reduce CO_2 emissions by co-firing coal with biomass fuels. During recent years, once-through supercritical (OTSC) CFB technology has been developed, enabling the next stage in CFB development to proceed to medium-scale (<500 MW_e) utility projects, with net efficiencies near 45% (LHV). However, scaling up the technology further to 600-800 MW_e with net efficiency of 45-50% (LHV) is needed to fulfill the future requirements of utility operators.

Carbon capture and storage (CCS) offers the potential for major reductions in CO_2 emissions of fossil fuel-based power generation in the near term, provided the required regulatory framework for transportation and storage is created, and incentives can provide solid return on the major investments required. Foster Wheeler Global Power Group is developing its Circulating Fluidized Bed (CFB) technology to incorporate Flexi-Burn™ combustion, in order to provide a CCS-ready solution. The Foster Wheeler "Flexi-Burn™" concept enables the plant to be operated either with or without carbon capture. This paper presents the existing status of CFB technology with respect to boiler efficiency and fuel flexibility. The main advantages of CFB technology for CCS carbon ready technology and a development plan for the Flexi-Burn™ CFB are also presented.

Introduction

Ample energy is needed to sustain robust economic growth, to enhance our national security, and to protect our environment. Over 50% of power generation in the United States is generated from coal-fired power plants even as the percentage of renewable energy supply increases. The United States has an adequate resource base of fossil energy, and coal is expected to remain the leading fuel source for power generation for a long time.

At modern power plants, the traditional pollutants can be well-controlled. Efficiency and environmental performance are key issues when considering either repowering existing power plants or building new power plants with high efficiency steam cycles. High efficiency means a lower fuel requirement per unit of plant output, and as a result, lower levels of ash discharge and gas emissions, including CO_2. Supercritical (SC) steam cycles provide high plant efficiencies together with a proportional reduction in gas pollutants. After waning in the 1980s, electric utility interest in SC cycles has revived in the United States. The advantages of SC and USC (ultra supercritical) steam temperatures up to 620˚C (1150˚F) in efficiency improvement and in emission reduction have been demonstrated or evaluated at a commercial scale. The interest in future is to pursue even more advanced steam conditions, such as 700˚C (1300˚F) to further increase efficiency, resulting in reduced emissions.

CFB steam generator technology has proven to be excellent in fuel flexibility and in co-combustion of bio-fuels which can further reduce CO_2 emission profile. Plant sizes up to 300 MWe are in operation today. In recent years, the once-through supercritical (OTSC) CFB has been developed enabling medium-scale, 500 MWe class units (such as the Lagisza SC CFB boiler, currently under construction) with net efficiencies over 42% (HHV) However, scaling CFB further to a size of 600-800 MWe is needed to fulfill the requirements of utility operators.

FW is continuously working on advancing the efficiency, and co-combustion capability of biomass and coal in CFB boilers. Both steps provide a technical and economical solution to the CO_2 issue in the near term. CO_2 removal is a necessary process for a long term approach. Oxy-combustion CFB is one of the proposed technologies for CO_2 removal. The CO_2 in flue gas is concentrated in the oxy-combustion process, where the fuel is burned with a mixture of near pure oxygen and circulated flue gas, instead of air. The absence of air nitrogen produces a flue gas with a high concentration of CO_2 that is ready for sequestration after cleaning of other non-CO_2 species and compression.

The high efficiency requirement becomes more critical for CO_2 removal by oxy-combustion, because for a given power generation or steam turbine size, a high efficiency reduces the amount of coal to be fired, which results in a lower O_2 requirement from air separation unit (ASU), less CO_2 gas to be processed in downstream CO_2 compression and purification unit (CPU), and less storage volume for CO_2 end sequestration. With this reduced penalty, the high efficiency power plant, when integrated with CO_2 removal, can generate more power and thus lower the power derating due to CO_2 removal.

As units become larger in size, they can represent a large fraction of a utility's output, and hence the need for high reliability increases. Since CCS adds additional systems and equipment to a plant, and since each of them have their own reliabilities, the overall plant reliability can be maximized by enabling a plant to continue to generate power if the other parts of the CCS system (e.g. capture, transport or storage systems) were down. The Foster Wheeler Flexi-Burn™ boiler approach allows the same boiler to be fired either in air-mode or in oxy-mode and capable of smoothly switching while online, thereby maximizing plant reliability and operational flexibility.

Ultra-Supercritical CFB

Reduction of greenhouse gas emissions relies, in part, upon increasing power generation efficiency, the end user efficiency, and greenhouse gas removal. It has become a major challenge for power producers and technology suppliers. One of the main approaches to reducing emission from power plant is to increase efficiency. Co-firing of biomass or other CO_2-neutral fuels in highly fuel-flexible CFB boilers also provides a near-term solution for CO_2 reduction.

Foster Wheeler and Endesa, together with a group of companies in Europe, have performed a study for an 800 MWe power plant with USC CFB (Ref-1). This group has developed a conceptual CFB boiler design concept to better understand the feasibility of large CFB boiler design. Independently, Foster Wheeler has also started a boiler design with an emphasis of determining the effect of configuration on part load performance for such a 660 MWe SC CFB boiler at a steam temperature of 620˚C (1150˚F). Earlier, a conceptual design study for an 800 MWe was conducted to investigate the technical feasibility and economics of the USC CFB boilers. This study was supported under the U.S. Department of Energy Cooperative Agreement No. DE-FC26-03NT41737 at 400 MWe and 800 MWe nominal plant sizes (Ref-2).

Preliminary studies show that the scale-up of boiler components to 800 MWe is possible for furnace, solids separators, and fluidized bed heat exchangers (INTREX™). The actual scale-up of the dimensions and size of plant components required is quite moderate due to the modular approach adopted for the CFB boiler design (Figure 1).

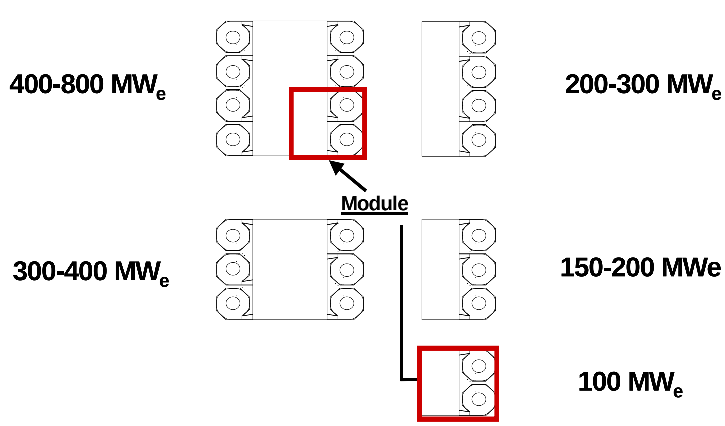

Figure 1: Modular design of CFB boiler

In once through SC boilers using vertical, multi-pass construction, the inside surface of the vertical tubes can be roughened, or rifled, to prevent the departure from nucleate boiling and dry-out that can result in elevated local tube metal temperatures and tube failures. Since CFB furnace combustion temperatures are relatively low and uniform, compared to those in pulverized coal furnaces, the heat fluxes to its furnace enclosure walls and the ratio of the CFB's peak to average heat flux are considerably lower (Figure 2). Because CFB furnace heat fluxes are relatively low and uniform, its tubes can operate with low water mass flow rates and still be protected from dry-out.

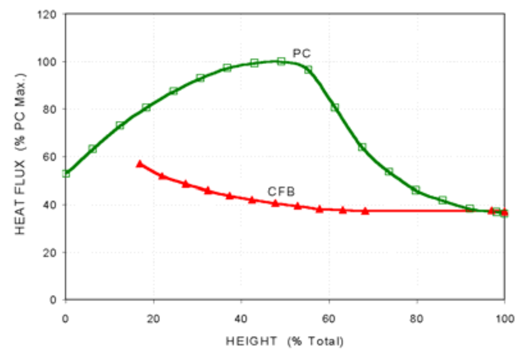

Figure 2: Heat flux comparison

Maintaining high separation efficiency in the CFB boiler's solids separators is a key to achieving high combustion efficiency, reduced limestone consumption, and high sulfur capture efficiency. As large CFB boilers use the modular building blocks (Figure 1), proven in smaller size units, there is no major scale-up issue, especially since Foster Wheeler has already provided multiple CFB boilers with separators installed on opposing walls of modules.

The number of fuel feeding and limestone injection points required by large units will be based on the number of modules, with each of the modules having been proven in smaller units. The same applies also for air distribution and start-up burners. Other auxiliary equipment, such as fans, conveyors, feeders, air heaters, baghouse filters, etc. are similar to those used in large PC power plants, which means that there will be no scale-up issues in the auxiliary systems.

After passing through the furnace solids separators, the nominal (870ºC) 1600ºF flue gas of a large CFB boiler will be cooled in a heat recovery area (HRA) consisting of convective tube bundles and walls used for superheating, reheating, and feedwater preheating (economizer); the arrangement will be typical of large PC boilers and poses no major scale-up issues.

The INTREX™ has been applied to support the increased superheat and reheat duties of high efficiency power plants. The INTREX™ is located directly under the solids separators (Figure 3). The solids collected by the separators pass through the INTREX™ cells (external solids circulation), transfer heat to the immersed tube bundles, and return to the furnace via aerated lift legs. Slots can be provided in the lower furnace walls adjacent to the INTREX™ cells to allow bed hot solids from the lower furnace to fall into INTREX™ cells (internal solids circulation), which increases the temperature of the bed, thereby increasing heat transfer. They should not pose a scale-up issue since these

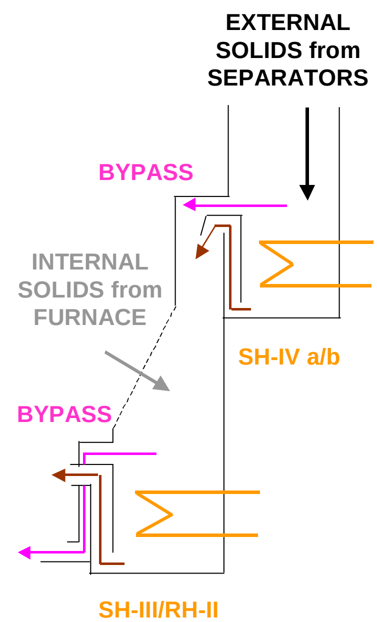

Figure 3: INTREX arrangement

exchangers provide a dense "package" of highly efficient heat transfer surfaces and have been utilized on several Foster Wheeler CFB boilers.

Because of the low furnace temperature, and the vigorous solids circulation, the CFB furnace heat transfer rates are lower, more uniform, and more predictable than those in pulverized coal units. The CFB boiler also has many ways to allocate heat transfer surfaces, plus several options for controlling main and reheat steam temperatures; e.g. flue gas proportioning, steam bypass, solids bypass, solid fluidization, and spray water attemperation. Figure 4 shows the options for heat transfer surface locations and for reheat temperature controls for SC CFB boilers.

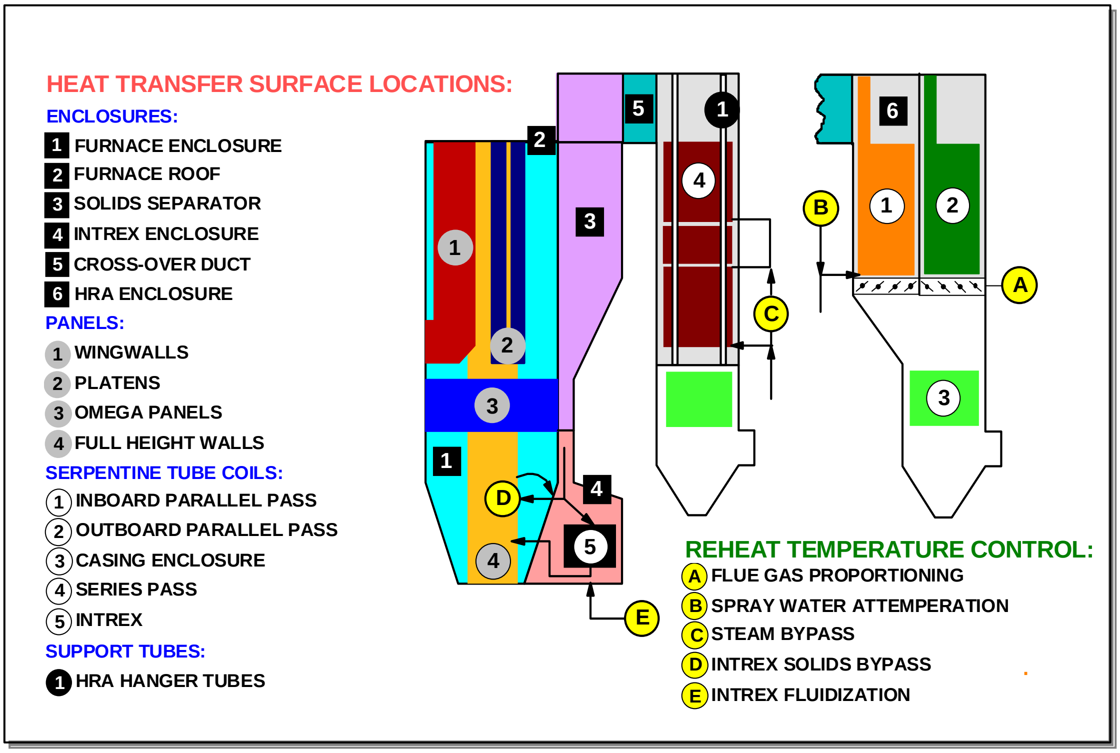

Figure 4: Heat transfer surface locations and reheat temperature control options

Despite their significant increase in size over current operating CFBs, USC CFB boilers reflect conventional design practices and can be built with existing technology. The overall performance and economics of the USC CFB plants have been determined, and like their present sub-critical designs, they are found to be competitive with comparably sized PC power plants while offering operating advantages of increased fuel flexibility, reduced emissions, and the ability to burn low calorific value fuels.

Flexi-Burn™ CFB Boiler

When CO_2 capture and sequestration (CCS) is required, oxy-combustion CFB technology offers the potential for near zero emission power production from fossil fuels. Foster Wheeler is developing Flexi-Burn™ CFB technology, which is the most feasible solution for meeting future CCS requirements (Ref-2, 3 & 4). Figure 5 shows a block diagram of an oxy-combustion power plant, which consists of an ASU, boiler (CFB or PC), steam cycle, and downstream CO_2 CPU. Oxygen from ASU is mixed with recycled flue gas for fuel combustion and boiler operation, instead of air. This produces CO_2 rich flue gas ready for sequestration after purification and compression.

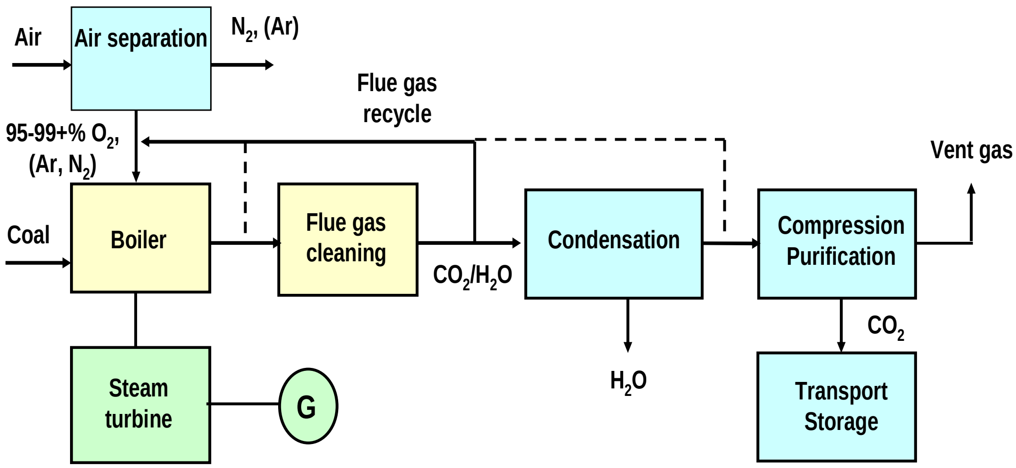

Figure 5: Block diagram of oxy-combustion power plant

Combustion with oxygen differs from combustion with air, in that it produces different gas compositions and can lead to high temperatures, unless flue gas recycle and/or increased solids cooling is used. The fundamental change in flue gas composition affects its properties, as listed by Table 1, where both gas density and thermal capacity increase. The high CO_2 and high water content of the oxy-mode flue gas increases both the gas density and the thermal capacity. As a result, the oxy-mode flue gas can absorb approximately 35% more heat per unit of gas volume, compared to the air-mode flue gas, and will carry the heat downstream to the convective heat transfer area of the boiler.

Table 1 Flexi-Burn™ Flue gas Properties

	Gas density (lb/ft3)	Specific heat (BTU/lb-°F)	(Gas density) * (Specific heat)
Air-mode	0.2936	0.2982	0.0876
Oxy-mode	0.3637	0.3245	0.1180

More power could be potentially generated by firing more fuel, due to the increased heat transfer under the same gas velocity in oxy-mode. The extent of firing more fuel has to be checked against the heat flux or the waterwall temperature, and the capacity of auxiliary equipment, such as the solids feeding system. The extra steam generated by firing more fuel may be extracted and be applied to drive CO_2 compressors, which will be more efficient and reduce cost, compared to similar electrically driven loads.

One option in designing an oxy-combustion boiler is to operate at higher temperatures by using a minimum amount of flue gas recycle, which reduces gas flow rates and the auxiliary power requirement from both the FD and ID fans, as well as corresponding boiler size. This reduced size boiler also introduces a challenge in the arrangement of heating surfaces, especially for the high efficiency SC and USC boilers, where more superheat and reheat surfaces are required. As a result this option is best left for Greenfield plants with new boiler designs, operated exclusively in oxycombustion mode.

Another option, the Flexi-Burn™ approach, is to operate the boiler under near the same conditions as air-firing by recycling the correct amount of flue gas. With this option, the adiabatic flame temperature is similar to air-mode under similar O_2%v level and gas velocity. Therefore it requires less or even no changes to the boiler design. For CFB, this option offers the right solid circulation to maintain the boiler performances, such as high combustion efficiency, optimized limestone consumption, and high sulfur capture efficiency, as well as better INTREX™ heat exchanger performance. This option also offers enough space for arrangement of heating surface for such a SC or USC CFB boiler. Most importantly, this option allows the boiler to be operated either in air-mode or in oxy-mode (Flexi-Burn™), and be capable of switching online between two modes without shutdown for physical change after initial installation. Such a plant could be even flexibly operated either with or without CO_2 capture upon demand, for instance depending on the price of CO_2 allowances and electricity.

Flexi-Burn™ CFB technology is being developed for existing boilers as a retrofit solution, for new capture-ready boilers to be modified for CCS in the future, and for greenfield power plants integrated with CCS. Design of Flexi-Burn™ power plants calls for case-specific optimization of the performance and economics. Normal boiler designs can be applied if the O_2%v is chosen so that the adiabatic combustion temperature is close to that of air-firing.

Foster Wheeler is currently adapting the Flexi-Burn™ concept to its CFB designs. Along with the development of CFB technology from small-scale to large-scale SC boilers, in-house boiler design tools, enabling rigorous design and performance predictions of CFB for a variety fuels, co-firing ranges, and operating conditions, have been developed. These tools are being modified to include the specific features related to oxy-combustion. Development and validation of all the required submodels for oxy-combustions require significant efforts, involving experimental tests and comparisons with air-firing operation. Foster Wheeler has undertaken experimental testing with a group of other interested organizations for CFB oxy-combustion testing, at laboratory and pilot scales that cover a wide test range of fuels, O_2% firing, heat flux, material development, corrosion, emission level and control, and etc. The testing has provided information about the differences between air-firing and oxy-firing, and the acquired knowledge is being incorporated into Foster Wheeler's boiler design tools.

Foster Wheeler is continuously working with a group of companies and researchers to evaluate new boiler materials, with respect to mechanical strength and corrosion resistance at elevated temperature for USC boiler application. This research work has also been extended to oxy-fuel combustion conditions and environments, to prepare for the next step of high efficiency USC CFB power plant integrated with CO_2 removal.

Based on in-house experimental tests and pressurized CFB combustion experience, it has been found that the optimum temperature for in-bed sulfur capture shifts with better sorbent utilization (Figure 6) when the CO_2 partial pressure is high, resulting from the high total pressure and/or high CO_2 concentration. This shifting will potentially allow the CFB to operate at higher temperatures, yielding increased LMTD and heat transfer coefficients, which allows a CFB boiler to operate at higher efficiency, when applied to the SC and USC CFB power plants integrated with CO_2 removal.

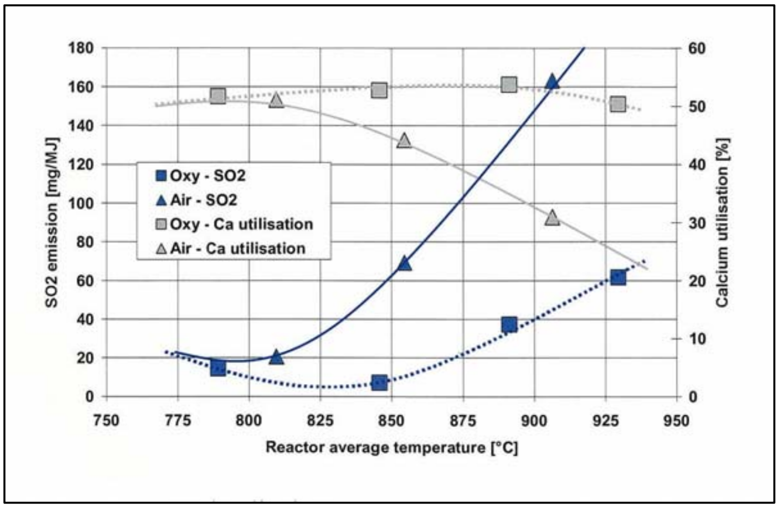

Figure 6: Comparison of SO_2 emission and Ca utilization

A fully integrated CCS demonstration project, based on the Foster Wheeler Flexi-Burn™ CFB boiler design, has been proposed for the Jamestown (New York) Board of Public Utilities by a team lead by Praxair, Inc. The plant has a gross output of combined heat and power of about 50 MWe equivalent. The captured CO_2 will be purified and stored in underground saline formations near the site. The Flexi-Burn™ CFB boiler design allows the plant to operate in air-mode (for low cost operation), or in oxy-mode (for CCS). Compared with a conventional air-fired unit, the major differences are the addition of ducts for flue gas circulation, mixers for O_2 injection, and low pressure economizer for recovering low-grade heat for condensate.

Endesa Generación (ENDESA) has evaluated and continues to survey different technologies related to CCS. ENDESA findings indicate that the supercritical Flexi-Burn™ CFB technology, with a capture rate above 90% of the CO_2 emissions, can be a mature option for commercial use by 2020. ENDESA is developing a 500-MW_e Flexi-Burn™ CFB project, working with Foster Wheeler, the main technology developer, in alliance with Praxair for the supply of the air separation unit (ASU) and CO_2 CPU. The Flexi-Burn™ CFB commercial demonstration plant is expected to be in operation by 2015.

The preliminary design of the Flexi-Burn™ CFB power plant has been completed, and continuing work aims at more extensive and detailed knowledge and designs. Figure 7 compares the flue gas temperature profile of the Flexi-Burn™ SC CFB under air-mode and oxy-mode operation. The preliminary results indicate:

- The furnace remains unchanged, but internal heat surfaces may be modified
- The total gas flow rate and O_2%v level are similar to air firing
- The rotary air heater is retained
- Preheated oxygen can be mixed with heated recycled flue gas just before boiler
- Effect of oxygen purity is small on boiler design, but significant on CO_2 purification
- Air ingress has significant effect on CO_2 purification

The emission control for Flexi-Burn™ is relatively easy due to its reduced flue gas volume flow, with higher concentration of pollutants. When compared with air-mode operation, only about 20-30% of the flue gas exits from boiler in oxy-mode operation, and flows to CO_2 CPU. Only about 5% of the gas will be purged as vent gas from CPU to stack, after most of the CO_2 has been removed at low temperature. The emission control system also benefits from gas circulation back to the boiler similar to re-burn and gas cooling processes in CO_2 CPU. However, the sulfur may need to be removed before CO_2 CPU, if it is restricted from flowing with CO_2 to the pipeline for storage.

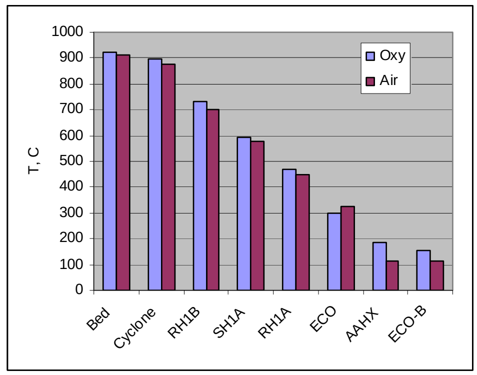

Figure 7: Flue gas T-profile comparison

This Flexi-Burn™ CFB approach would reduce risks due to failures of ASU, CPU or pipeline and storage equipment, by allowing the boiler to be operated in air-mode without shutdown. In principle, it also allows more flexible operation depending on power demand and CO_2 capture requirement.

The lower fuel firing rate afforded by a high efficiency large size Flexi-Burn™ CFB boiler offers not only reduction in emissions, including CO_2, but also a reduction in auxiliary power requirements by the ASU and CPU equipment. The Foster Wheeler Flexi-Burn™ approach offers the same CFB boiler to be used either in air-mode or in oxy-mode, which is capable of switching online, enhancing its reliability.

Summary

Higher efficiency power plants require less fuel to be fired, resulting in a proportional reduction in emissions. This study has shown that a conventional CFB boiler design approach can apply to USC steam conditions. The proven high efficiency CFB boiler with SC or USC steam parameters offers an excellent solution for coal-fired power plants with CO_2 reduction, for both repowering and Greenfield cases. CFB technology has excellent fuel flexibility and offers the opportunity for further reduction of CO_2 emissions by co-firing coal with biomass.

The Foster Wheeler Flexi-Burn™ approach presents a solution for oxy-combustion, where a boiler can be fired either in air-mode or in oxy-mode. It allows the same boiler to be operated at near the same gas velocity and oxygen level as air-mode. The capability of online switching between two modes allows operation with and without CO_2 capture, which increases its availability.

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