Utility-Scale Flexi-Burn™ CFB Power Plant To Meet the Challenge of Climate Change

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ABSTRACT

Coal combustion-based power generation faces continuing environmental challenges to reduce pollutant emissions, especially more recently, carbon dioxide emissions. Carbon-dioxide capture and storage (CCS) offers the potential for major reductions in carbon-dioxide emissions of fossil fuel-based power generation in the fairly short term, and oxy-fuel combustion is one of the identified CCS technology options. Foster Wheeler is working on reduction of carbon-dioxide with its integrated Flexi-Burn™ CFB technology. Through proper configuration and operation, the Flexi-Burn CFB is capable of on-line switching between air and oxy-fuel mode.

The proven high efficiency circulating fluidized-bed (CFB) technology, when coupled with air separation units and carbon purification units, offers a solution for carbon dioxide reduction both in re-powering and in greenfield power plants. CFB technology has the advantages of relatively low, uniform furnace heat flux, good fuel flexibility and offers the opportunity to further reduce carbon dioxide emissions by co-firing coal with bio-fuels.

Development and design of an integrated 500 MWe-class Flexi-Burn CFB steam generator and balance of plant system has been conducted for both air mode and oxy-fuel mode. Through proper design, the same steam generator can be switched from air mode to oxy-fuel mode without the need for unit shutdown for modifications. Foster Wheeler is working with the largest Spanish utility company, Endesa Generación, which plans to demonstrate a 500 MWe scale Flexi-Burn OXY-CFB for CCS within the European Union's SET Plan CCS demonstration program. The Flexi-Burn CFB system incorporates features to maximize plant efficiency and power output when operating in the oxy-firing mode through firing more fuel in the same boiler. This paper provides an update of the recent work by Foster Wheeler to bring utility-scale Flexi-Burn CFB technology to market, in order to enable cost-effective CCS.

INTRODUCTION

Coal combustion-based power generation faces continuing environmental challenges to reduce pollutant emissions, especially more recently, carbon dioxide emissions. Oxy-fuel combustion, as shown in Figure

1, is one of the methods suggested for removing carbon dioxide from the exhaust gases of a power plant, such as a PC or a CFB steam generator. Oxy-fuel combustion is based on combusting carbonaceous fuel with oxygen, to produce carbon dioxide and water vapor as the main components of the exhaust gas. Thereby, the carbon dioxide can be captured relatively easily from the exhaust gas, without having to separate it from a gas stream having nitrogen as its main component, as when combusting the fuel with air. Part of the exhaust gas needs to be recycled to the furnace for temperature control, and to achieve sufficient furnace gas velocity to operate the circulating fluidized bed (CFB) with solids circulation.

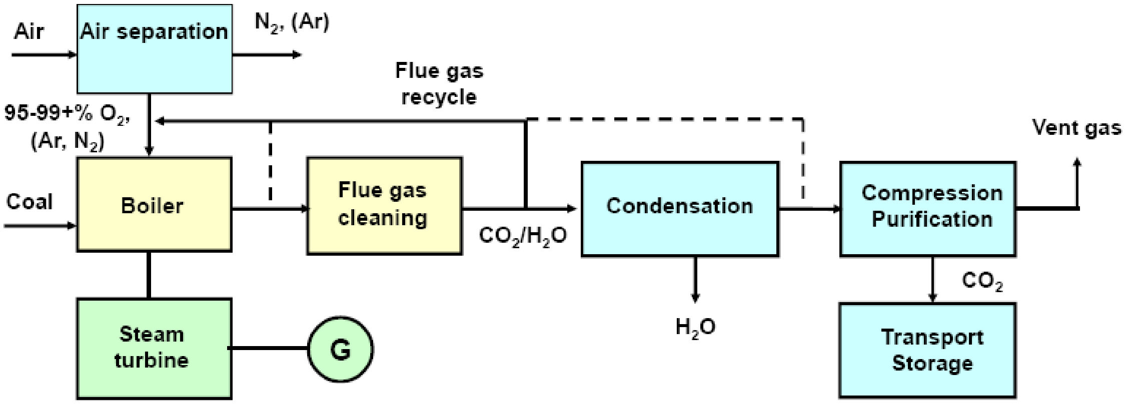

Figure 1 Basic Diagram of Oxy-fuel Combustion

Since oxy-fuel combustion is still a developing technology, it is advantageous to design oxy-fuel combustion boilers, where the combustion conditions are selected to be similar to those of air-fired combustion. This is done by recycling exhaust gas back to the furnace to provide an average O_2 content of 20-28%v. Due to the similarities of air combustion and moderate O_2 level oxycombustion, oxy-fuel steam generators can be built by modifying existing air-firing boilers. Due to the uncertainties related to oxy-fuel combustion, capture and storage of carbon dioxide, the regulatory credit (or penalty) for CO_2 emissions and increasing need for carbon capture ready power plants, there is a need for Flexi-Burn™ boilers, i.e., boilers which can be changed from air-firing to oxy-fuel combustion, preferably without any changes in the actual construction. With such a Flexi-Burn boiler it is also possible to have the maximum power output by using air-fired combustion mode during high load demand, such as summer, weekdays and daytime, and apply oxy-fuel combustion with CO_2 removal at other times. In order to generate power more economically by an oxy-fuel combusting boiler system, there is a need for an improved system design and operation for minimizing the loss of produced power, and minimizing the requirement of building new power plants to compensate the power loss due to CO_2 removal (Ref 1, 2). The Flexi-Burn CFB design concept, as shown in Figure 2, addresses these needs. (Ref 3, 4, 5, 6).

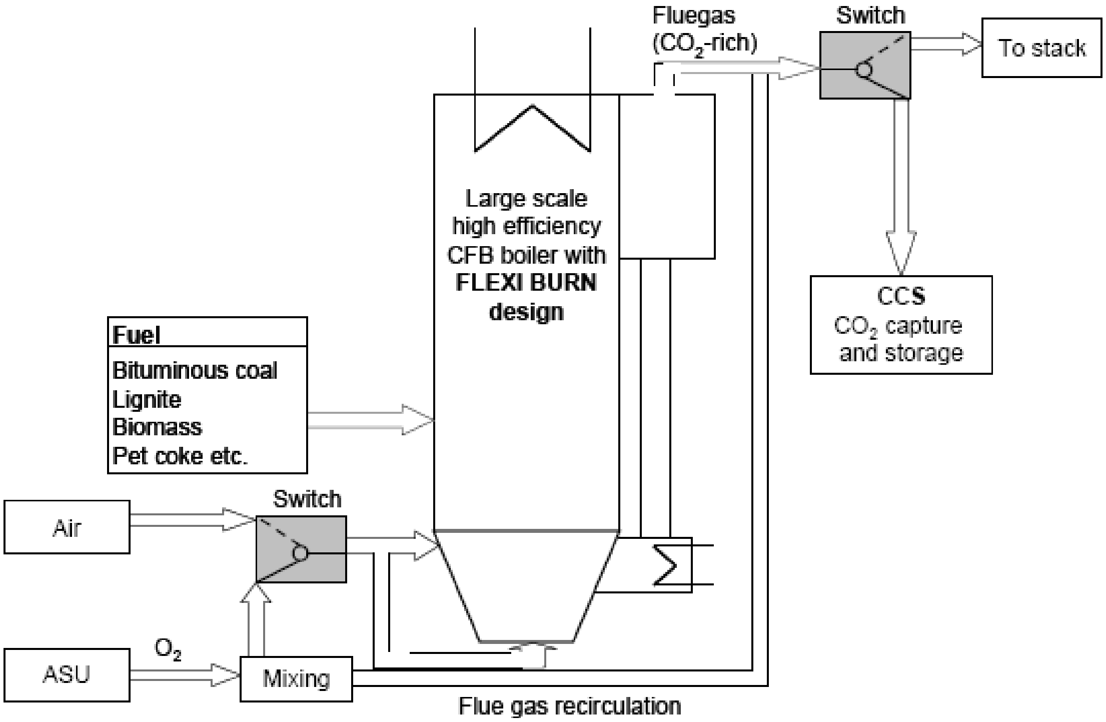

Figure 2 Flexi-Burn™ CFB Concept

To enhance power generation operability and availability it may be advantageous to operate a Flexi-Burn boiler in air-firing mode, when, for example, the air separation unit (ASU), CO_2 purification/compression unit (CPU), or CO_2 storage system is unavailable. Due to different requirements and demands, the power generation and the steady state electrical power supply should always be readily decoupled from the upstream oxygen supply and the downstream carbon dioxide processing (Ref 4).

Combustion with oxygen differs from combustion with air mainly as a result of the different gas compositions. The fundamental change in fluegas composition affects its properties, as listed by Table 1, where both gas density and thermal capacity (specific heat) are changed. A challenge for a Flexi-Burn boiler is that its heat distribution varies with gas properties and operations. At a given gas velocity, due to high gas density and thermal capacity contributed from carbon dioxide and water vapor in fluegas, more heat (about 35% more in oxy-fired mode than air-fired mode as seen from Table 1) is absorbed by the flue gas and carried to the downstream heat recovery area (HRA).

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

To obtain suitable heat flux at the furnace waterwalls, the combination of CFB boiler operating gas velocity and temperature need to be maintained at certain levels. One can maintain the correct furnace heat flux by increasing firing temperature through reduced gas mass flow by recycling less flue gas. For a greenfield case, this can be done by designing a reduced size boiler to keep a desired gas velocity. But a reduced boiler size approach cannot be applied as a retrofit. When firing in air-mode, both air and fuel fed to such a reduced size boiler are limited and less power would be generated, which leads to a boiler which is suitable only for oxy-firing mode after conversion. Increasing firing temperature can enhance heat flux, but it also leads to an increase of waterwall temperature, which may require tube materials to be upgraded. Given the choice of upgrading tube materials to increase gas side heat flux or to produce high steam temperatures, it is generally more economical to produce higher steam temperatures due to increased steam cycle efficiency. There is a significant amount of materials research being conducted related to increasing main steam conditions, such as to 1300 F, in order to achieve greater power generation efficiency. This work will allow deployment of super-critical and ultra-super-critical Flexi-Burn CFB boilers (Ref 6).

Increasing power generation output is the key to minimize power derating and cost due to CO_2 removal. One can either reduce power consumption caused by (ASU+CPU) through improvements, or increase power generation output with the same boiler to reduce the power derating. It is noted that in comparison with oxy-firing, the boiler optimized for air-firing seems oversized for oxy-firing due to potentially reduced gas volume flow. The object of the present paper is to provide an oxy-fuel combusting boiler system, and a methodology for using the boiler system so as to minimize the loss of produced power, and to minimize the modifications for the retrofit option.

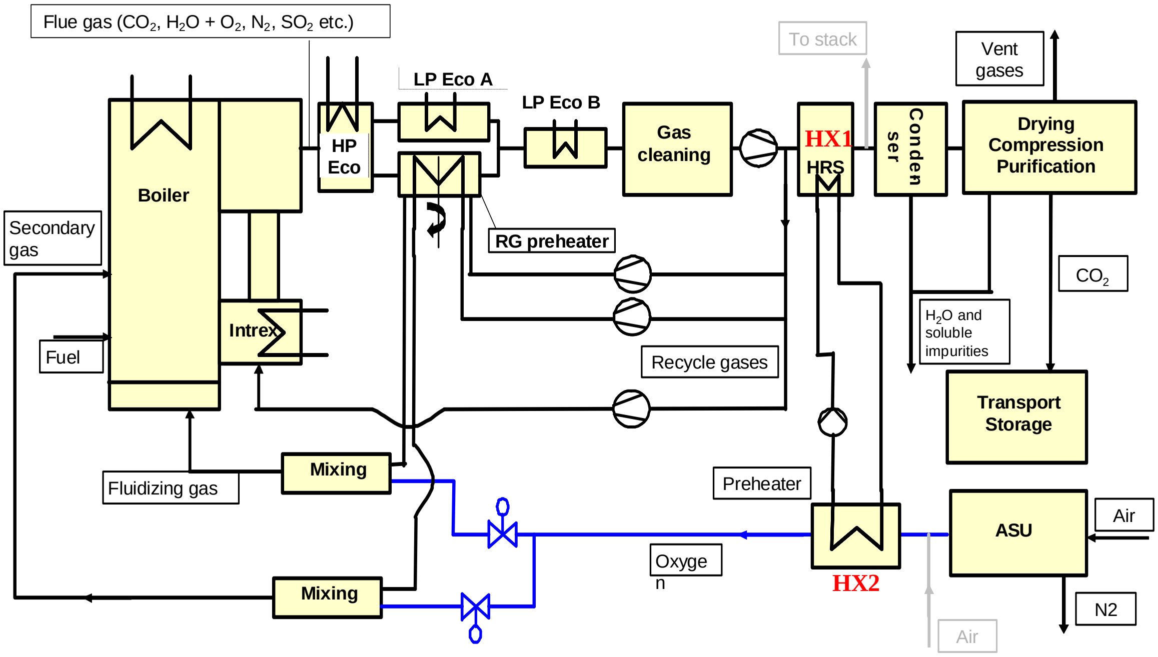

Figure 3 Process Flow Diagram of Flexi-Burn™ CFB Steam Generator Island

FLEXI-BURN™ BOILER CONFIGURATION

Figure 3 presents a process flow diagram (PFD) of a CFB power plant designed for both air-fired and oxy-fired operations with the capability of Flexi-Burn and operation switching. As shown in Figure 3, oxygen from the air separation unit (ASU) after preheating is mixed with recycled flue gas and fed to the boiler with solid fuel and sorbent for sulfur capture. The flue gas from boiler after passing through heat recovery area (HRA) is cooled down by a combination of regenerative air-air heat exchanger (AAHX) and low pressure economizers (Figure 3, LP-ECO-A, and LP-ECO-B). Most of the flue gas after the ESP and ID fan, in wet and hot condition without moisture condensation, is recycled and recuperated with hot flue gas in the AAHX. The heated recycled gas streams are then mixed with pre-heated oxygen to form the “primary air” and “secondary air” and fed to the boiler, where the mixing ratio can be adjusted for better performance. The balance of the flue gas is cooled down in the HRS (heat recovery system, a wet-end heat exchanger made of plastic material, where low-pressure circulated water recovers the low-grade heat from the flue gas and uses it to pre-heat combustion air in air-fired mode). Part of the recycled gas, without mixing with O_2, is pressurized by HP fan as “high pressure” and functions as seal and aeration gas for CFB operation.

The balance of the fluegas from the HRS is cooled by a direct water quenching (may be combined with post sulfur capture) before being forwarded to the CO_2 purification/compression units (CPU), where the remaining moisture in fluegas is removed to a ppm level by adsorption. This dry flue gas is purified by CO_2 condensation. Both liquid CO_2 and vent gases are flashed and used as cold sources to cool the inlet fluegas. The purified/flashed CO_2 streams are compressed to the final pressure and cooled down before discharged to the CO_2 pipeline.

In oxy-mode, the lack of nitrogen increases the concentration of moisture and sulfur in fluegas, which raises the acid gas dew point. To avoid acid gas condensation, the fluegas temperature to the ESP in the oxy-mode is controlled by a combination of low pressure economizers (LP-ECO-A and LP-ECO-B).

RESULTS

The development of this Flexi-Burn approach was based on a conceptual design of a 460 MWe supercritical CFB power plant, modified for oxy-fuel combustion, as shown in Figure 4. The incorporation of the Flexi-Burn concept means that the boiler must be operable at, or near, full load in air-firing mode and in oxy-firing mode without modification, when it is built.

In both air-firing and oxy-firing modes, the Flexi-Burn boiler may be operated at a slightly higher furnace temperature than normally used for air-firing. Part of the reason for this increased temperature is due to the increased quantity of fuel fired, and another reason is to ensure that the limestone calcination temperature is exceeded in spite of the high CO_2 partial pressure in oxy-mode. Further pilot-scale experimental tests are required to validate sulfur capture models in oxy-mode. The gas velocity is similar regardless of firing mode. The oxygen level in the flue gas is controlled to be the same in both modes to ensure the right combustion performance.

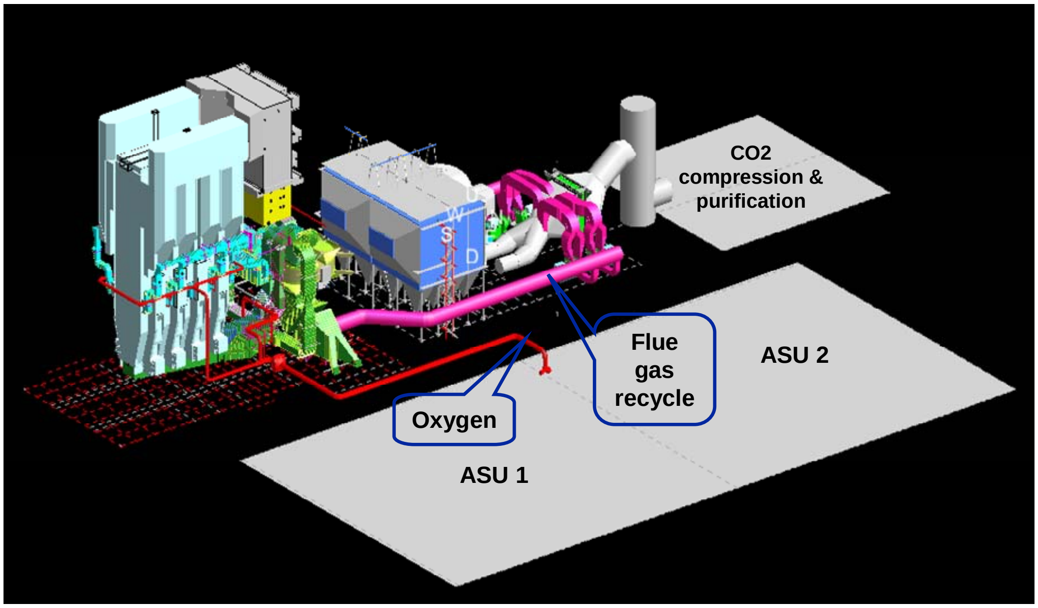

Figure 4 Retrofit Design of 460 MWe CFB Plant with Flexi-Burn™ Technology

In system level evaluation, the following assumptions were applied:

- O_2 purity as 96.5%v
- Air in-leakage as 1.5%v
- Fixed boiler and downstream sizes for Flexi-Burn
- The same O_2%v in flue gas for both modes
- Hot gas recycled before moisture condensation
- Recycled gas recuperated by air-air heat exchanger
- Steam extraction to ASU and CPU for chilling and regeneration
- CO_2 compressor driven by extracted steam

The Foster Wheeler in-house CFB design tools were utilized for this development work. After engineering design tuning and iterating for both air-firing and oxy-firing modes, a Flexi-Burn CFB boiler is configured, designed and integrated as shown by Figure 3. It needs to be mentioned that this Flexi-Burn boiler differs in arrangement of surface area from that of the original air-firing boiler. Some modifications are required such as adding or removing tubes as compared with regular air-firing boiler design. But no modifications are required after the boiler is converted for Flexi-Burn operation.

Figure 3 shows the resultant flue gas temperature profile for both air-firing and oxy-firing operation modes. It can be seen that the bed temperature is slightly higher in oxy-mode than that in air-mode. Fluegas exhaust temperature to the ESP is increased in oxy-mode to avoid acid gas condensation. The fluegas temperature exiting the HPECO is lower in oxy-mode due to the cold inlet feedwater temperature as result of turning-off some of feedwater heaters to allow the HPECO to pickup more heat from the fluegas. Correspondently, the steam generation rate is increased by about 10%, which means that steam flow is increased to all superheat/reheat heat exchangers.

Table 2 Results for Comparison

Performance	air	oxy
Feed, kg/s		
Coal	42.8	52.2
Sorb	7.9	10.8
Air/oxy	427.2	102.6
Power, MWe		
Gross	463.8	514
Aux ST	15.7	69
ASU		79
CCU		57
Aux	44	53
Net	436	393
eff, % (HHV)	42.26	31.29
eff, % (LHV)	43.49	32.20
dCO2, kg/s	0	117
derating, %		9.8

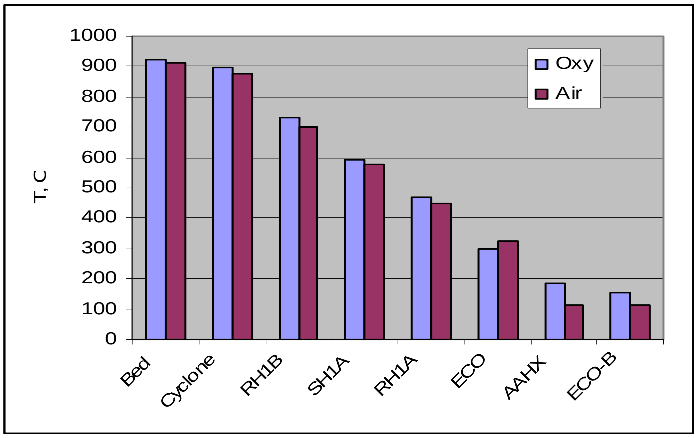

Figure 5 Flue Gas Temperature Profile

For comparison, Figure 6 shows the resultant flue gas maximum velocity at different locations from both air-firing and oxy-firing modes. As it can be seen from the Figure 4, they are almost the same as the result from present Flexi-Burn approach. It is noted that gas velocities are slightly higher in oxy-mode than in air-firing mode at most of the locations due to temperature (Figure 3), except at the AAHX, where part of fluegas split to the ECO-A is increased for a better heat recovery in oxy-firing mode.

Table 2 summarizes the power plant performance of the Flexi-Burn CFB with and without CO_2 removal. Part of the extra steam, generated from firing more fuel and saved from less steam extraction to feedwater heaters, is extracted and used to drive the CO_2 compressor by auxiliary steam turbines, which produces about 69 MW. The plant auxiliary power is increased by about 20% due to operation for firing-more fuel, such as fuel handling.

The increase in firing is 52.2/42.8=1.22, or a 22%. The power loss for CO_2 removal from (ASU+CPU) is (79+57)/1.22=111 MW (or 111/436=26% derating), and the specific power for CO_2 removal is 332 kWh/tCO_2. By firing more fuel, the net power loss is reduced to only 43 MW or less than 10% derating as listed in Table 2. This low power derating is important in reducing building new power plants due to CO_2 removal penalties.

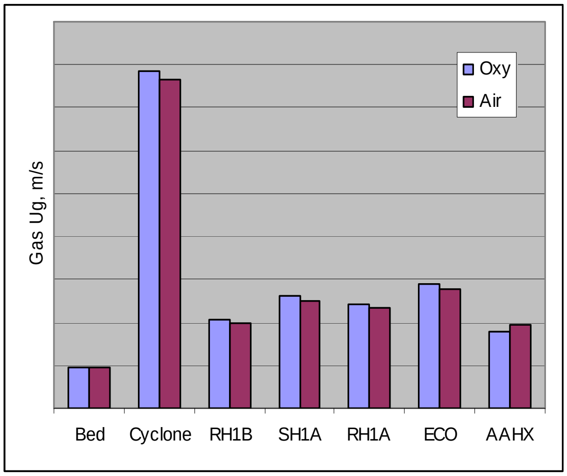

Figure 6 Comparison of Gas Velocity

The O_2%v in the gas fed to boiler in oxy-mode is about 23-24%v, which is close to the 21%v from air-mode. This ensures that the difference in operation between air-mode and oxy-mode is small. The O_2 is preheated to about 120 C and mixed with recycled fluegas after recuperation (Figure 1). The O_2 content in the “primary air” and “secondary air” can be different which will be tested in future pilot plant runs.

Regardless of the amount of fluegas recycled, the net fluegas flow to the CPU plant is almost constant. The fluegas flow to the CPU will increase with increase of fuel firing. Therefore ASU, CPU, and fuel feeding capacities have to be increased. However, fluegas recirculation and associated auxiliary power remains unchanged during firing more fuel. Flexi-Burn also means less modification to the existing boiler when conversion from air-mode to Flexi-Burn mode.

Since part of the CO_2 is vented out with impurities, the CO_2 removal is about 116.7 kg/s out of 121.3 kg/s from fuel combustion and sorbent calcination, which leads to a CO_2 removal efficiency as 96.2%. This high efficiency partly results from less air in-leakage and increased oxygen purity (96.6%). The final CO_2 stream has purity as 95.1%v and is pressurized to 139 bar (2000 psia) as a liquid or supercritical fluid.

It is been noted that the direct penalty 332 kWh/tCO_2 (ASU+CPU) operated under a 96.5% O_2 purity and 1.5% air in-leakage is almost the same as the literature data 333 kWh/tCO_2 (Ref 1) operated under 95% O_2 purity and 3.0% air in-leakage, but the present case has a better CO_2 removal efficiency of 96.2% as compared with 90.6% from Ref 1.

The cooling tower duty increases from 500 to 800 MWth or a 60% increase because of extra cooling duty from firing more fuel, and from flue gas cooling, compressor inter-stage and post cooling. This is substantially more than the 22% increase in coal flow rate. Part of this duty increase, about 200 MWth, comes from the cooling requirement of the ASU+CPU plants. The rest comes from a reduced steam extraction to feedwater heaters as result of heat recovery from fluegas cooling. This cooling duty change from oxy-mode requires physical modification of the cooling tower.

Gas cooling is required before, during and post compression. The low-grade heat from these cooling operations may be recoverable depending upon system integration. As heat recovery shares the gas cooling, the cooling water requirement is reduced when heat recovery is applied. The number of stages of compressor affects the heat integration, where the increased compressor discharge temperature (CDT) results from less compression stages and leads to better heat recovery and more power at the generator at a cost of increased compression power. The equivalent power gain has been calculated on the basis of steam savings for the same heating duty to water side. The degree of low-grade heat recovery may be limited by temperature difference or “pinch point”. To compensate for this, less compression stages may need to be used. In the present integration, almost all of the condensate needs to be extracted for heat recovery. Less compression stages could potentially be more optimal.

Due to application of the HRS in both oxy-mode and air-mode operation, there is no relative gain in oxy-mode from flue gas cooling before CO_2 compression, which means the efficiency difference is enlarged in comparison with the case without the HRS, due to increased efficiency by use of the HRS in air-mode. For this reason, the oxy-mode absolute efficiency may be a better measure of performance than the efficiency drop from air-mode.

It is noted that the end steam flow through steam turbine has been increased from 207 kg/s in air-fired case to 260 kg/s in oxy-fired case, which is about 26% more as compared with the 10% increase in main steam flow due to firing more fuel. More sections of low pressure steam turbine or a different size of steam turbine is required to accommodate this flow if the extra steam is not extracted to drive CO_2 compressors.

Steam driven feed water pumps have been widely applied in modern power plants, where extraction steam is taken from the IP/LP crossover or a nearby extraction point. The advantage of this approach is in that (1) it reduces the low pressure end steam flow and has a better steam turbine efficiency, and (2) it reduces all power associated with generator, transformer, motor, frequency converters, and gear loss. Based on the study for a 500 MW power plant (Ref 2), the savings from steam driven feedwater pumps could be 12% as compared with those driven by motors. About 6 MW net saving would be obtained out of 56 MW for CO_2 compression with four stages, if steam driven CO_2 compressors were applied. The corresponding end steam flow through main steam turbine would be reduced. Due to the issues of startup time requirement and upstream location of ASU, steam driven air compressors for ASU have not been included. For CO_2 compressors driven by extracted steam, this is not a problem as they are located downstream of boiler with much less startup time.

For this Flexi-Burn boiler, the part load condition (32-35%) with the same steam flow rate for both air-mode and oxy-mode have been evaluated and checked for the once-through operation (Benson point). The O_2 content in the fluegas was maintained as the same at full load for both modes. At the part load, the excess O_2 rises in air-mode, but stays constant in oxy-mode because oxygen fed and gas recycled can be adjusted separately. This is based on a control concept where the desired gas velocity is maintained by manipulating fluegas recycle, and the O_2 is adjusted by the demand of fuel combustion. This low excess O_2%v at part loads saves ASU power.

More oxy-mode experimental tests and large scale demonstrations measuring emissions, heat transfer, materials, and fouling are required for validation of design tools and solutions. 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 O2 injection, and low pressure economizer for recovering low-grade heat for condensate.

CONCLUSIONS

System level development, oxycombustion equipment integration, and CFB boiler design for the Flexi-Burn concept have been performed for a power plant with CO_2 removal, in support of Endesa Generación's plans to demonstrate a 500 MWe scale Flexi-Burn CFB for CCS. The Flexi-Burn design makes a power plant capable of on-line switching between air-firing and oxy-firing modes. In addition to potential improvement in the plant availability, the Flexi-Burn boiler approach potentially leads to a solution for peak power by operating the plant in air-fired mode and for CO_2 removal in oxy-fired mode when power demand is low. By this approach, fewer new power plants will be required to compensate for the power derating due to CO_2 removal. Also, as result of adopting a advanced design concepts, the plant power derating may be reduced from about 25% to only about 10%, and the net power is increased from 322 to 393 MWe. This also helps to reduce the need for building additional new power plants to compensate for the power derating due to CO_2 removal.

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