Global primary energy demand is growing, and is likely to continue growing during the next years. Energy projections made by the World Energy Council, the International Energy Agency (IEA) and the US Energy Information Administration give similar pictures of future energy requirements, mainly supplied by fossil fuels. Although it is expected that the share of the fossil fuels in the energy mix will decline in the future, the dominant role of fossil fuels will remain for decades to come, which entails large emissions of CO\text{2} if new policy measures are not endorsed. Carbon Capture and Storage technologies (CCS) have the potential to reduce CO\text{2} emissions into the atmosphere, providing by 2050 up to 20\% of the CO\text{2} reduction required to combat climate change.

In this context, one of the current European initiatives in terms of R&D&D on Carbon Capture and Storage (CCS) and Clean Coal technologies (CCTs) is the Technology Development Centre for CO\text{2} Capture and Storage, or es.CO2 Centre, which is supported by the Spanish Government through The Fundacion Ciudad de la Energia (CIUDEN). CIUDEN is a research and development institution created by the Spanish Administration in 2006 and fully conceived for collaborative technology development on CCS and CCTs. The es.CO2 Centre incorporates the world’s most advanced equipment for the development of capture processes through oxycombustion based on two combustion technologies: Pulverized Coal (PC) and Circulating Fluidized Bed (CFB).

Foster Wheeler is the technology provider of the 30 MWth oxy-CFB unit, which achieved first fire on coal in September 2011 and underwent initial oxy-mode commissioning in December 2011. This CFB unit design allows multiple fuels to be tested either under conventional combustion with air or under oxy-fuel conditions (Flexi-Burn\textsuperscript{®} concept), and combines CFB’s intrinsic advantages (fuel flexibility and low SO\text{2} and NO\text{2} emissions) with oxygen-firing for CCS.

This paper focuses on initial operational experiences of CIUDEN’s 30MWth oxy-CFB facility. During the preliminary tests in spring 2012, and the first test campaign in summer 2012, an extensive amount of operational data were acquired for four fuels and fuel mixtures. Results from first operational experiences are extremely promising. This oxy-CFB installation, which is the first of its class, will provide a real basis for the design and operation of flexible and competitive oxycombustion facilities at demonstration scale. Results achieved here aim to validate the
design of a future 330 MWe supercritical Oxycombustion Power Station (OXY-CFB-300 Compostilla Project) intended to demonstrate CCS technology in commercial scale.

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**Keywords**: Carbon Capture and Storage; Circulating Fluidised Boiler; Oxycombustion

1. Introduction

Carbon Capture and Storage (CCS) technologies have the potential to reduce overall climate change mitigation costs and increase flexibility in reducing CO2 emissions. Energy projections made by the World Energy Council, the International Energy Agency (IEA) and the US Energy Information Administration give similar pictures of the dominant role of fossil fuel in the future primary energy global demand and the importance of CCS as part of the portfolio of solutions to reduce GHG emissions [1 - 3]. IEA calculation puts CCS in a critical role as a least-cost pathway to reaching the 450 ppm scenario where the role of CCS increases after 2030, up to 19% of needed reductions against the baseline in 2050 [4].

The Europe 2020 Strategy for smart, sustainable and inclusive growth includes headline targets that set out where the EU should be in 2020, one of which relates to climate and energy. This way, Member States have committed themselves to reducing GHG emissions by 20%, increasing the share of renewables in the EU's energy mix to 20%, and achieving the 20% increase in energy efficiency target by 2020. In February 2011 the European Council reconfirmed the EU objective of reducing GHG emissions 80-95% by 2050 compared to the 1990 baseline, in the context of necessary reductions according to the Intergovernmental Panel on Climate Change [5].

The Technology Development Centre for CO2 Capture and Transport, or es.CO2, is located in the province of Leon (North-western Spain) supported by the Spanish Government through The Fundacion Ciudad de la Energia (CIUDEN). CIUDEN is a research and development institution created by the Spanish Administration in 2006, with the aim of collaborative technology development in Carbon Capture and Storage (CCS) and Clean Coal Technologies (CCTs). The capital investment in CIUDEN’s Technology Development Centre is more than 100 M€, which indicates the relevance of the installation.

The es.CO2 Centre, shown in Figure 1, incorporates the world’s most advanced equipment for the development of capture processes through oxycombustion, based on two combustion technologies: Pulverized Coal (PC) and Circulating Fluidized Bed (CFB). A more detailed description of the Centre is given elsewhere [6 - 8].

Foster Wheeler is the technology provider of the oxy-CFB unit, which achieved first fire on coal in September 2011 and underwent initial oxy-mode commissioning in December 2011. This CFB unit design allows multiple fuels to be tested either under conventional combustion with air or under oxy-fuel
conditions (Flexi-Burn®† concept). Particular requirements of a testing unit are required, including additional instrumentation to support a wide range of measurement points, and the option to vary the operating conditions with the maximum flexibility and versatility possible.

This paper focuses on initial operational experiences of CIUDEN’s 30MWth oxy-CFB facility during the boiler commissioning and test campaigns conducted. The configuration combines CFB’s intrinsic advantages (fuel flexibility and low SOx and NOx emissions) with oxygen-firing for CCS. It must be pointed out that the CFB technology appears to be ideally well suited to oxygen-firing combustion [9].

Results from first operational experiences are extremely promising. During the preliminary tests in spring 2012 and the first test campaign in summer 2012, an extensive amount operational data were acquired for four fuels and fuel mixtures. The ongoing test campaign is scheduled to continue through March 2013. It was observed that the automatic transitions between air and oxy-mode were smooth and relatively short, with typical transition times of about 30-40 minutes (air-oxy-or oxy-air). Significant reductions in emissions of NOx and SOx have been achieved operating under oxycombustion conditions. Preliminary results indicate that limestone injection, for in-bed capture of SOx, performed more efficiently in oxycombustion. Further analysis to quantify this result in relation to S content of the fuel and limestone used is required.

This oxy-CFB installation, which is the first of its class, will provide a real basis for the design and operation of flexible and competitive oxycombustion facilities at the demonstration scale, thus accelerating the deployment of CCS technologies. The results achieved here aim to validate the design basis of a future 330 MWe supercritical Oxy-Combustion Power Station (OXY-CFB-300 Compostilla Project) intended to demonstrate the CCS technology in commercial scale.

† Flexi-Burn is a trademark of Foster Wheeler Energia Oy, registered in the US, EU, Finland
2. CIUDEN’s CFB boiler description

The CIUDEN 30 MWth CFB boiler (Figure 2) is a natural circulation, balanced draft, circulating fluidized bed boiler, which is designed to test circulating fluidized bed combustion using either air or a mixture of recirculated flue gas and oxygen as oxidant. The CFB boiler operates on the circulating bed principle where solid material is separated from the flue gas stream in a hot separator, which moves the solids downward to the loop seal through the cyclone down-comer.

The CFB unit design allows either the operation under conventional combustion with air, or under oxycombustion conditions (Flexi-Burn® concept). The size of this experimental boiler is sufficient to allow the scaling of the results to commercial units, while maintaining the relatively low investment cost and operating expenses. As a result, multiple fuels and operating conditions can be economically tested in this experimental unit [10, 11].

![Fig. 2. 30 MWth CFB Boiler installed at CIUDEN’s Technology Centre for CO2 Capture and Transport](image)

The design of this CFB boiler considers the particular requirements of a testing unit, which include a wide range of measurement points and the option to vary the operating conditions with the maximum flexibility and versatility possible, meeting the necessary requirements and boundary conditions. Maintenance and inspection procedures of all unit components have been optimized, and the additional instrumentation, beyond what is normally included on a CFB, has been added, in order to gather additional data from future operation. As a result, this oxy-CFB boiler is a versatile and flexible boiler testing and demonstration platform, which will be instrumental in the development of larger-scale oxy-CFB technology.
Main features and components of this CFB boiler are illustrated in Figure 3. The major components of the boiler are the combustion chamber, solids separator, loop seal and the INTREX™ superheaters, located in a separate fluidized bed chamber. The CFB also includes provisions for SNCR for NOx reduction and fly-ash reinjection.

Solid material is circulated through the cyclone downcomer to the loop seal. Part of this circulated solid material is returned directly to the furnace and the rest is cooled in a final superheater box before entering the furnace for combustion temperature control. Ammonia injection in the cyclone provides proper gas mixing, at the proper reaction temperature, to reduce NOx emissions. Limestone injection is utilised to control SO2 emissions within the environmental permitted level and make-up sand is used, when needed, to maintain the proper bed characteristics. Fine solids (fly ash) and flue gas exit at the top of the cyclone and are directed to the convection section of the boiler. Part of the flue gas is recirculated to the boiler by the respective oxidant fans. Recycled fly ash is fed to the lower part of the furnace in order to increase retention time and reduce unburned material. Bottom ash is removed from the bottom of the furnace through one ash drain to maintain furnace material balance and bed material quality. Control of bed inventory and quality is an essential function of the CFB combustion system.

Depending on the operation mode, the oxidant required for combustion is obtained by mixing the following gases:

- Recirculated combustion gases, cleaned and cooled in the gas treatment system
- Ambient air
- Oxygen.

The oxidant required is divided into independent streams, each with a specific function, entering the furnace at different levels:

- Primary oxidant through the grid fluidizes the bed provides low oxygen atmosphere
Primary oxidant through upper nozzles provides the remaining oxidant for appropriate lower combustion atmosphere. Secondary oxidant at different levels provides an oxidant atmosphere to complete the combustion process and control the combustion emissions. High pressure gas assures solids return to furnace by fluidizing loop seal. Transport gas helps fuel and limestone to enter the furnace at the appropriate velocity.

Feedwater is heated by the economizer and steam is produced in a natural circulation evaporator circuit comprising downcomers, evaporative surface, riser tubes and steam drum. Saturated steam from the drum flows to the convection cage, which is the first superheating stage. Steam is then led to the two superheaters of the INTREX with three attemperation stages.

The fuel flexibility of the CIUDEN oxy-CFB boiler allows the utilization of a wide range of coals with simultaneous co-firing of biomass. In oxycombustion mode, fuel is burned with a mixture of recirculated flue gas and oxygen instead of air. The absence of air nitrogen produces a flue gas stream with a high concentration of CO2, and therefore facilitates capture [11].

3. Experimental results

The 30 MWth Flexi-Burn® CFB unit was first fired with coal in September 2011. As part of the commissioning activities (4th quarter 2011 through 2nd quarter 2012), the first functionality tests in this CFB boiler were carried out satisfactorily burning anthracite coal from the El Bierzo region of Spain (with petcoke blends), in a conventional combustion mode using air as oxidant. Oxy-CFB conditions were first tested in December 2011. Data recorded from the various process parameters (bed temperatures, unburned carbon, etc.) were in line with expectations. This Flexi-Burn® CFB boiler reached full load in a stable manner under varying operational conditions. The functionality test runs were conducted during the 1st half of 2012. Integrated operational tests with the CO2 Compression and Purification Unit (CPU) were achieved in October 2012, after the commissioning of a CPU by Isolux Corsan with technology provided by Air Liquide.

The unit has been successfully run in both conventional air-mode, as well as oxy-mode. Four types of fuels and blends (anthracite, petcoke, sub-bit, biomass) with different compositions have been already tested during more than 1300 hours of operation, of which 920 hours were under oxycombustion conditions. In addition, two types of limestone were tested as sulfur sorbent.

Flexi-Burn® operation (including switching between air and oxy modes) has been demonstrated during the 1st quarter of 2012 using Spanish anthracite (Cupo del Bierzo) with ash content of 33-35 w-% (d.s.), sulfur content of 1-1.2 w-% (d.s.) and heating value of 19.5-22 MJ/kg. During the preliminary testing, the process variables have been steam load, combustion temperature, limestone feed rate and oxygen content in oxidant streams. During these tests adjustments on the control system enabled the transition between air-mode and oxy-mode to be successfully performed.

The curves, as shown on Figure 4, indicate that the transition can be automated and goes smoothly in both directions. This test demonstrated that the unit was able to achieve a minimum level of 80 vol-%(dry) CO2 level in flue gas. This level of CO2 corresponds to an air in-leakage of approximately 3%. Actions are in progress to further reduce this figure.
Fig. 4. Transition (air-oxy-air) during Flexi-Burn® operation of the oxy-CFB boiler

The emissions curve, shown in Figure 5, presents the NOx (including NO2) for the same period as shown in Figure 4. The NOx results confirm the general understanding, and previous small pilot results, that NOx is reduced in oxy-mode, compared to air-mode.

Fig. 5. NOx emissions during Flexi-Burn® operation of the oxy-CFB boiler

During oxy-fuel mode testing, SO2 emissions control was readily achieved by feeding limestone. A limestone feed rate of 10% of the fuel feed, resulted in significant reduction of SO2 emissions, in some cases below 200 mg/Nm³. CO emission was low and remained steady, indicating stable and efficient combustion in oxy mode throughout the load range. The tests also confirmed the results of the small pilot tests performed earlier, which showed that the SO2 capture is temperature-dependent. At low furnace temperatures (<870°C), the capture performance is reduced, hence, requiring more limestone to achieve the same SO2 level. This confirms that SO2 capture occurs via a direct sulfation mechanism. Kinetics of direct sulfation is slower compared to calcination-sulfation, which is typical in air combustion and also in oxy combustion at higher furnace temperature (i.e. above the calcinations temperature). Preliminary
indication is that limestone performed slightly more efficiently in oxy combustion. Future testing is necessary to confirm the results and optimize the performance.

The experimental results are to be used for model validation, and to generate the knowledge-base to support the scale-up to the commercial size units. Operation in oxycombustion mode provides a CO$_2$–rich flue gas stream, suitable for testing and demonstrating process equipment needed for CO$_2$ purification and compression. The test data being collected will also enable the impact of oxycombustion operation on combustion, emissions, and materials corrosion of boiler heating surfaces to be evaluated.

Additionally, the experimental results from CIUDEN’s unit aim to validate the design basis of a future 330 MW$_{e}$ supercritical Oxy-Combustion Power Station (OXY-CFB-300 Compostilla Project) intended to demonstrate the CCS technology in commercial scale. The Compostilla OXY-CFB-300 Project is one of the 5 CCS demonstration projects funded under the European Energy Programme for Recovery (EEPR) of the EU. The Project is based on a future 330 MW$_{e}$ Circulating Fluidized Bed (CFB) supercritical oxy-combustion plant, with CO$_2$ storage in a deep geological formation. The first phase of the Project, granted by the EEPR program and coordinated by the Spanish utility ENDESA, includes all studies needed on the technology, costs, financing, regulatory and permitting required, prior to the Final Investment Decision by the 2013 for the construction phase [12, 13].

4. Conclusions

The paper includes a description and update on initial operational experiences of the oxy-CFB 30 MW$_{th}$ system installed at CIUDEN’s Technology Development Centre for CO$_2$ Capture and Transport, located in Northwestern Spain. The CIUDEN’s Centre is a large scale facility aimed to develop CCS technologies, the only facility in the world with two large pilot boilers capable of burning a wide range of coals, biomass and pet coke under conventional combustion and oxycombustion conditions.

The oxy-CFB configuration combines CFB’s intrinsic advantages (fuel flexibility and low SO$_x$ and NO$_x$ emissions) with oxygen-firing for carbon capture and storage. Foster Wheeler is the technology provider and equipment supplier of the Flexi-Burn® Circulating Fluidized Bed unit in CIUDEN’s Centre. The unit, which is the first of its class, achieved first fire on anthracite coal in September 2011 and oxycombustion operation in December 2011. During the preliminary tests in spring 2012 and the first test
campaign in summer 2012, an extensive amount operational data were acquired for four types of fuels and fuel mixtures (anthracite, petcoke, sub-bit and biomass). The ongoing test campaign is scheduled to continue through March 2013.

Results achieved from the test campaigns are extremely promising. Smooth automatic transitions between air and oxy-mode were observed, with typical transition times of about 30-40 minutes (air-oxy- or oxy-air). Significant reductions in emissions of NOx and SOx have been achieved while operating under oxycombustion conditions. Preliminary results indicate that limestone injection for in-bed capture of SOx performed more efficiently in oxycombustion. Further analyses and tested are ongoing in order to validate these preliminary results, and to optimise the design and some technical aspects related to oxy-CFB technology. In this regard, the availability of CIUDEN’s Centre as technology development platform with high flexibility and capabilities to allow the scaling of the results to commercial units is of utmost significance.

These results are to provide a real basis for the design and operation of flexible and competitive oxycombustion facilities at demonstration scale, thus accelerate the deployment of CCS technologies. In this way, results aim to be scaled up and used to validate the design of a future 330 MW supercritical oxycombustion Power Station (OXY-CFB-300 Compostilla Project) intended to demonstrate CCS technology at commercial level.

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