Development and demonstration of oxy-fuel CFB technology

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Synopsis

Reduction of CO_2 emissions is the key driving force behind the development and implementation of new solutions for energy production. One solution is circulating fluidized bed (CFB) combustion technology combined with a high-efficiency once-through water-steam cycle. Foster Wheeler's CFB technology is today commercially available in capacities up to 800 MW_e with ultra-supercritical steam parameters. Simultaneously, the Flexi-Burn® CFB technology is being developed to provide capability of flexible operation in air firing and oxy-combustion for carbon capture. CFB technology can offer an attractive solution for the reduction of CO_2 emissions, owing to advantages such as fuel flexibility and low emissions that the air-fired CFB technology offers today. Pilot test facilities provide information about the performance of CFB oxy-combustion technology, and the acquired knowledge is being incorporated in boiler modelling and design tools.

One of the European R&D initiatives on carbon capture and storage (CCS) is the Technological Centre for CO_2 Capture and Transport, which is supported by the Spanish Government through the Fundación Ciudad de la Energía (CIUDEN). CIUDEN is a research and development institution created by the Spanish administration in 2006 and fully conceived for collaborative research in CO_2 capture, transportation, and storage. The Technology Development Centre for CO_2 Capture and Transport comprises two technologies on oxy-combustion: pulverized coal (PC) and circulating fluidized bed (CFB). This paper will focus on the design and main characteristics of the 30 megawatt-hour thermal capacity (MW_{th}) oxy-CFB boiler.

Foster Wheeler is the technology provider of the Flexi-Burn CFB unit, for which commissioning has been completed in the first quarter of 2011. The CFB unit design allows operation either under conventional combustion with air or under oxy-fuel conditions. The size of this experimental boiler is sufficient to allow the scaling of the results to commercial units. In this way, multiple fuels and operating conditions can be tested economically. The results will validate the design of a future 330 MW_e supercritical Oxy-Combustion Power Station (OXY-CFB-300 Compostilla Project) intended to demonstrate the CCS technology at commercial scale.

The Compostilla OXY-CFB-300 Project is one of the six 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 CFB supercritical oxy-combustion plant, with CO_2 storage in a deep geological formation. The first phase of the project, granted by the EEPR programme and led by the Spanish utility ENDESA, includes all studies and characterization work needed on CO_2 capture, transport, and storage, as well the costs, financing, and regulatory and permitting required, prior to the final investment decision for the construction phase of the plant by the end of 2012.

Keywords
oxyfuel, CFB, once through steam cycle, supercritical steam, coal firing, pilot testing.

Introduction

Figure 1 shows a simplified process flow scheme of a power plant designed for both air-fired and oxygen-fired operation modes. It consists of an air separation unit (ASU), a high-efficiency steam cycle utilizing FW Flexi-Burn® circulating fluidized bed (CFB) boiler technology, and a CO_2 compression and purification unit (CPU). For oxy-fuel combustion, which is the primary operation mode, oxygen is mixed with recycled flue gases, which creates a mixture of primarily O_2 and CO_2 (and H_2O) used as oxidant in combustion instead of air. The absence of nitrogen produces a flue gas stream with a high concentration of CO_2, making it much easier to separate the CO_2. In the air-firing mode, which serves risk-mitigation purposes but may also be applied during high load demand, the ASU and CPU are out of service (or on standby) and the plant is operated like a conventional power plant, emitting flue gases to the atmosphere.

Research and technology development (RTD) activities for the Flexi-Burn CFB development

The RTD Framework

Foster Wheeler has been developing oxy-fuel CFB combustion since 2003 through:

**Flexi-Burn is a trademark of Foster Wheeler Energia Oy, registered in the US, the EU, and Finland

* *Foster Wheeler Energia Oy, Finland.*
† *Fundación Ciudad de la Energía, Ciuden.*
‡ *ENDESA Generación SA, Spain.*
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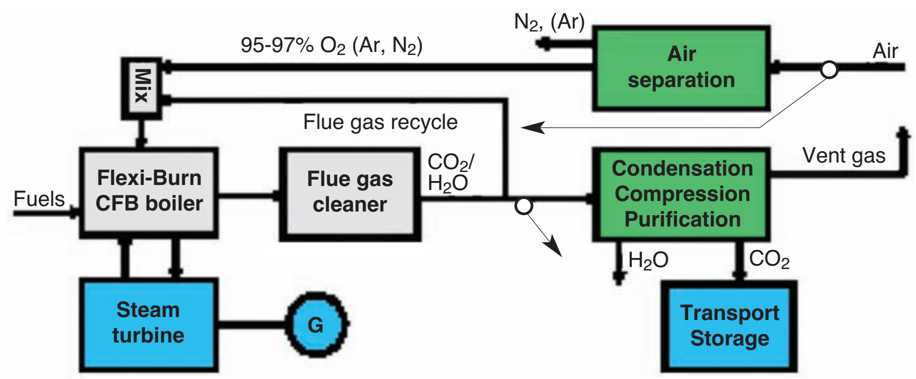

Figure 1—Schematic of a Flexi-Burn CFB power plant

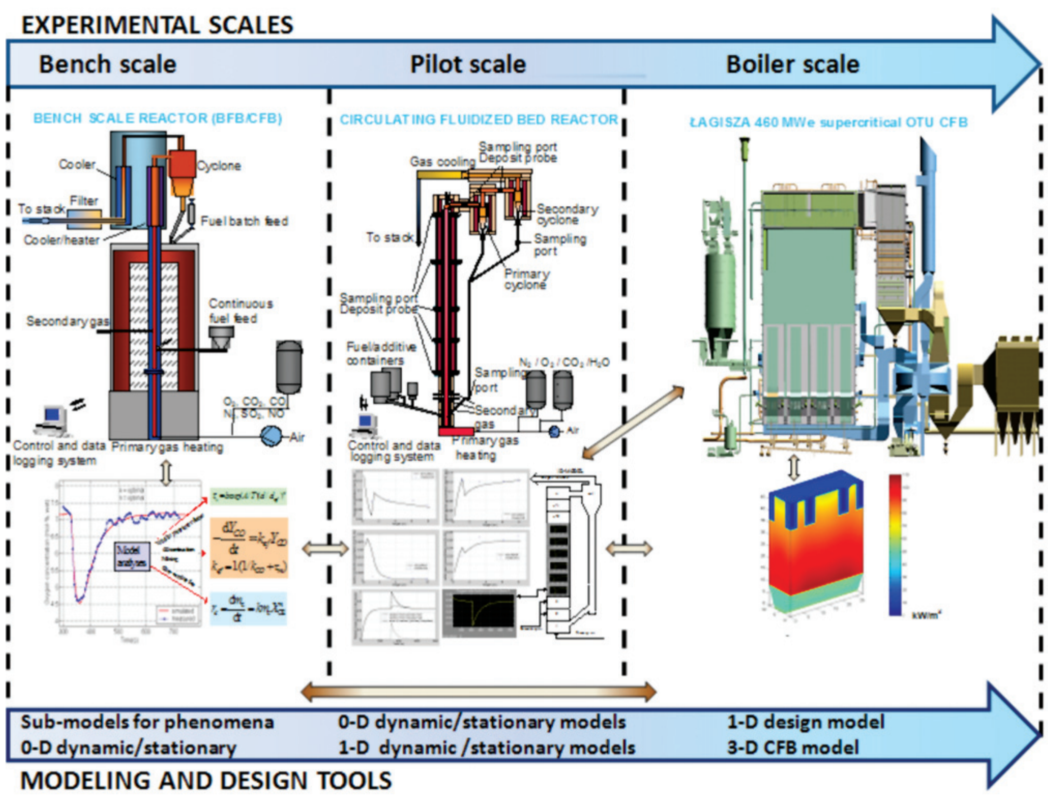

Figure 2—Scale-up approach based on integrated experimental and modelling work[1]

- ➤ Knowledge and design tool development
- ➤ Test activities (bench-scale (VTT), small CFB test rig (VTT), and ~0.8 MWth CFB pilot (CANMET))
- ➤ Conceptual and feasibility studies (boiler design).

In the development of Flexi-Burn CFB technology, FW applies an approach illustrated by Figure 2, which has been used in the scale-up of CFB boilers in the past two decades. Bench- and pilot-scale CFB furnaces provide well-controlled environments for studying different phenomena related to combustion, heat transfer, and emissions. Process understanding gained from small-scale experiments and modelling can be linked to designing of full-scale CFB boilers[1].

Even though the once-through (OTU) CFB technology has been commercially demonstrated for conventional air firing, additional efforts are required to ensure the technological applicability to oxy-firing. For this purpose, the framework of a powerful collaboration between ENDESA, CIUDEN, and *FOSTER WHEELER* has been established. Within this collaboration, the following main RTD activities will be executed:

- ➤ Test programme in the air-fired reference plant (Lagisza 460 MW_e OTU CFB)
- ➤ Small-scale pilot testing of oxy-combustion in the CFB process
- ➤ Characterization of the design fuels and limestone in air and oxy-fuel conditions in a laboratory-scale plant of around 0.8 MW_{th} at CANMET in Canada
- ➤ Validation tests at CIUDEN´s oxy-fired CFB at 1:30 scale

- Development of operating modes and control strategies of the fully integrated CIUDEN Technology Development Center for CO_2 Capture and Transport in Spain
- Developing models for optimizing the final design for oxy-combustion
- Economic and risk assessment studies.

Once-through CFB technology scale-up

The Polish utility company Południowy Koncern Energetyczny SA (PKE) selected Foster Wheeler Energia Oy's 460 MW_e supercritical CFB boiler in 2003 for their Łagisza power plant. The new 460 MW_e power unit of Łagisza was synchronized to the electrical network for the first time on 15 February 2009, and reached full output power of 460 MW_e on 10 March. Commissioning continued with fine tuning of the boiler controls and performance prior to the start of a 720 h trial operation. The Łagisza CFB power plan was handed over to the client on 27 June 2009.

After operating for more than 2 years, it can be stated that the operational experience of the Łagisza boiler has been excellent. Over the whole load range, the boiler has performed as designed, and operation has been steady and easily controllable. All performance targets were demonstrated during trial operation. Thus, Łagisza has validated Foster Wheeler's supercritical CFB design platform, providing a solid base for further units[3]. Based on continuous development work, including the experience from over 350 reference boilers in operation or under construction worldwide, the capability to offer supercritical CFB technology up to 800 MW_e scale with full commercial guarantees has been created. Recently Foster Wheeler has been awarded the design and supply of four 550 MW_e (gross megawatt electric) supercritical CFB steam generators for the Samcheok Green Power Project for Korea Southern Power Co. Ltd. (KOSPO).

The design and operating experience of the Łagisza unit will form the foundation for the development of the Flexi-Burn CFB technology. In support of this development, a field test campaign was carried out in 2010 in conjunction with project partners of the FP7 'FLEXIBURN CFB' project

Small pilot testing of oxy-combustion—the CFB process

FW has carried out several test campaigns at bench scale and small pilot scale since 2004 at VTT. In addition, FW has participated in several public projects in which fundamental understanding has been created on the oxy-fuel process and related phenomena. Bench-scale testing is well suited for producing data on specific combustion phenomena, whereas the pilot tests give process data on actual circulating fluid bed conditions. Results of these tests are presented in previous conference papers and presentations[1,2,4].

Characterization of the design fuels in a 0.8 MW_{th} scale CFB pilot facility

CanmetENERGY Technology Centre, Ottawa, (CETC-O) has retrofitted its 0.8 MWth CFB pilot plant for oxy-fuel combustion. The main components of the pilot plant (Figure 3) are the riser with an internal diameter of 0.406 m and an internal height of 6.6 m, hot cyclone, return leg, flue gas cooler, baghouse, and feeders for fuel and sorbent. Riser temperature is controlled with up to four water-cooled bayonet tubes, which can be inserted or retracted during operation by a motorized winch system. A natural gas start-up burner preheats the CFBC to the ignition temperature of the test fuel.

During retrofitting, a flue gas recycle line was added, including a recycle blower, a flue gas condenser, and pressure control and safety equipment. The flue gas is drawn from the exit of the baghouse. Oxygen from a storage tank is mixed with the recycled flue gas to maintain combustion in the CFBC. Operating parameters remain basically the same as in the air-firing mode. However, the facility is run under slightly positive pressure to prevent air in-leakage, and oxygen level in the combustion gas can reach 29 per cent. Flue gas from the CFBC is continuously analysed for CO_2, CO, O_2, SO_2, and NO_X. The system can operate[4] at temperatures up to 1000°C and superficial velocity of 4–6 m/s.

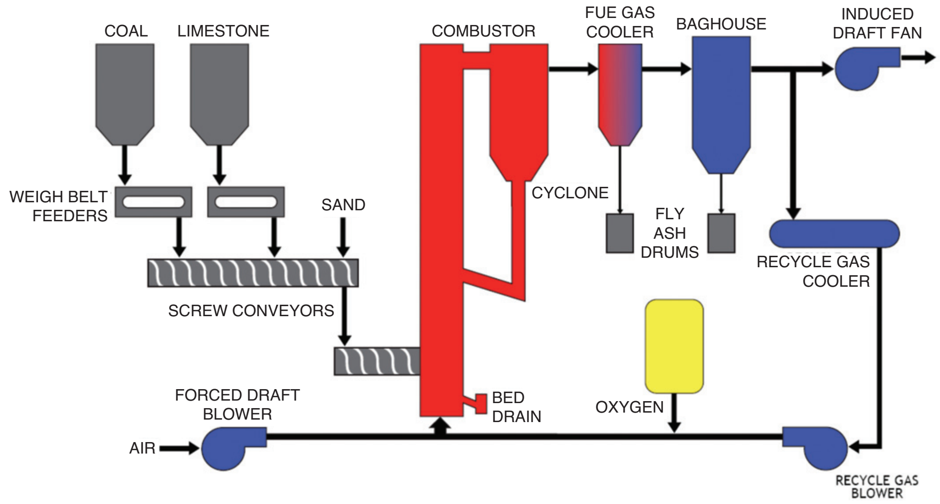

Figure 3—CanmetENERGY 0.8 MW_{th} oxy-fuel CFB combustion pilot facility

An extensive test programme to characterize the potential design fuels and sulphur sorbents for the planned 330 MW_e Flexi-Burn CFB demonstration boiler, was conducted with cooperation of FW, ENDESA, and CETC-O. The test campaign commenced in Fall 2009 and continued until the end of August 2010.

The test plan consisted of fourteen weeks of pilot-plant operation, including reference tests in air mode, followed by one or two weeks of testing in oxy mode. The typical varied test parameters were: firing rate, limestone feed rate (Ca/S ratio), combustion temperature, excess air, air distribution, and oxygen/recyle gas ratio (oxidant O_2).

Analyses of the test fuels are presented in Table I. In additon, the blends of both Spanish anthracite and petcoke and bituminous coal and Spanish lignite were tested.

The project provided plenty of data about the differences between oxy-fuel combustion and conventional combustion of different fuels. Phenomena of interest included combustion, firing rate, emissions-related issues, mixing, heat transfer, fouling, and corrosion. Figure 4 shows an example of the furnace temperature during one of the anthracite oxy-combustion tests. The combustion process was steady both in air and oxy-combustion operation. An example of results related to sulphur capture in a petcoke combustion test is shown in Figure 5. Sulfur capture efficiency was equal or better in oxy-combustion compared to air combustion.

The important conclusion is that no major issues that contradict previous assumptions and beliefs were identified during the tests. Hence, the oxy-fuel CFB technology continues to be an interesting option for CCS.

CIUDEN Technology Development Centre for CO_2 Capture and Transport

CIUDEN is a research and development institution created by the Spanish administration in 2006 and fully conceived for collaborative research in CCS and CCTs, thus contributing to the strengthening of the industrial and technological base in

Table I

Analyses of test fuels

	Proximate analysis, %			
	Anthracite	Bit. coal	Lignite	Petcoke
Moisture	6.1	6.0	21.8	6.2
Volatiles	7.3	25.9	30.8	10.1
Ash	34.3	14.9	33.0	0.8
Fixed carbon	52.3	53.2	14.4	82.9
Ultimate analysis (as received), %				
C	57.4	68.6	46.3	85.7
H	2.1	4.00	3.58	3.6
N	0.92	1.71	0.51	1.64
S	1.1	0.86	7.16	6.61
O	1.95	8.02	16.64	1.70
Higher heating value				
HHV, MJ/kg (dry basis)	21.7	27.3	17.9	34.6

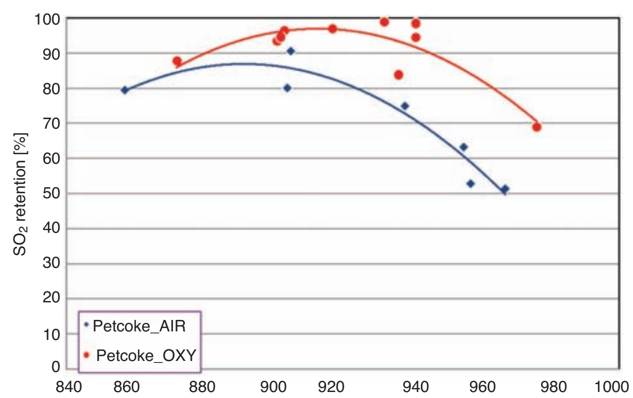

Figure 5—An example of SO_2 retention vs. bed temperature in air and oxy-combustion of petcoke

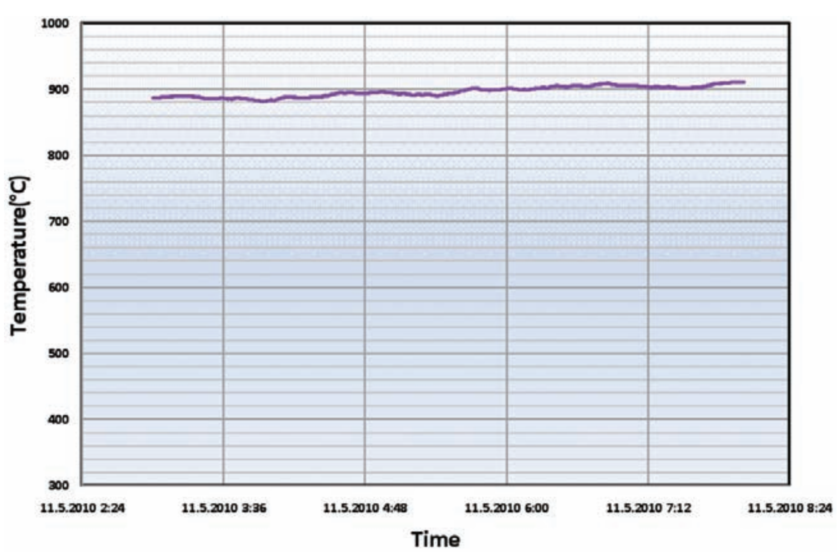

Figure 4—Temperature in lower furnace during an oxy-combustion test of anthracite demonstrates steady combustion process

Spain and by extension in Europe. CIUDEN´s main objectives within the CO_2 Capture Programme are the research, development, and demonstration of efficient, cost-effective, and reliable CCS and advanced CCT, as well as third-generation flue gas cleaning through the design and operation of CIUDEN's Technology Development Centre for CO_2 Capture and Transport (the es.CO_2 Centre)[5,6].

The es.CO_2 Centre features all necessary equipment to provide the CO_2 stream ready for transport at a 1:30 scale. Testing campaigns are to be performed jointly by the partners, aiming to arrive at a sound basis for the refinement of the incorporated technologies, especially the CFB under oxy-firing conditions, but also the dynamic behaviour of the complete unit. Through this approach the risks associated with the design and construction of a first-of-its-kind Flexi-Burn CFB boiler will be greatly reduced, thus resulting in lower uncertainties about costs and availability.

The Centre is located adjacent to the Compostilla II Power Plant. The configuration of the es.CO_2 Centre is flexible, modular, and versatile in order to test a wide range of operating conditions, including different coals and combustion conditions from air mode to oxy mode in independent but interconnected modules for simultaneous or separate operation. Figure 6 shows an aerial view of the es.CO_2 Centre with the main units indicated. A general description of the es.CO_2 Centre is found elsewhere[6-9].

Figure 7 shows a 3D model of the CFB boiler island with the main design parameters.

Figure 6—CIUDEN´s es.CO_2 Centre

Dimensions (m)	21x2.7x2.4
Power (MWth)	30 max
O_2 (kg/h)	8775
Flue gas recycle (kg/h)	25532
Flue gas (kg/h)	28800
Coal feed (kg/h)	5469
Limestone feed (kg/h)	720
Steam (t/h)	44.6
P(bar) / T (°C)	30 / 250

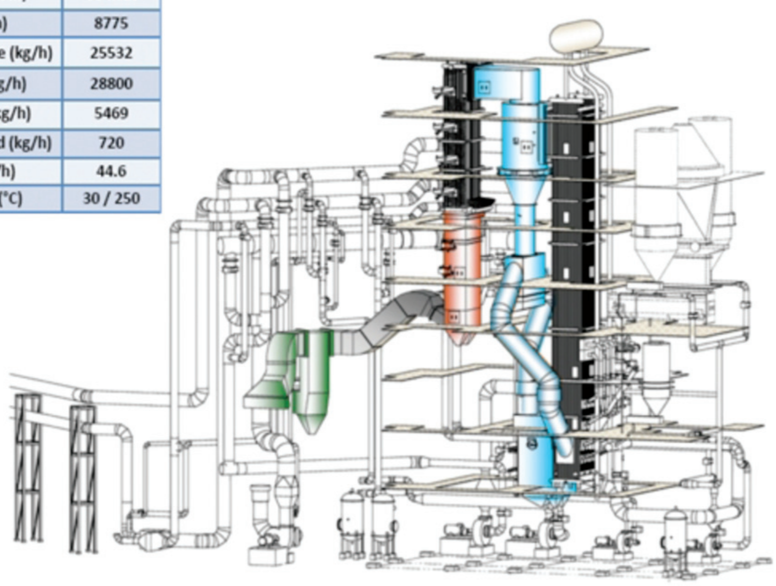

Figure 7_Flexi-Burn CFB Boiler at the es.CO_2 Centre

Table II

Main features of Compostilla Project

Capture technology
• 330 MW_e OXY-CFB supercritical boiler
• Wide design fuel range (domestic and imported), including biomass
CO_2 transport
• 12-inch / 16-inch underground pipeline, 150 km
• 5 500 t/day; ~ 120 bar
CO_2 storage
• Deep geological formation

OXYCFB300 Compostilla Project

The OXYCFB300 Compostilla Project is based on a CCS integrated commercial-size demonstration project, covering the entire CO_2 chain: capture, transport, and storage. The project is one of the six selected CCS EU demonstration projects co-funded by the European Commission's European Energy Programme for Recovery (EEPR) .

The overall Compostilla Project is based on a future ~330 MW_e CFB supercritical oxycombustion plant, with a dense-phase CO_2 transport line and final underground CO_2 storage in a deep geological formation. The main target of the OXYCFB300 Compostilla Project is to validate a fuel-flexible and competitive CCS technology at industrial level for a wide range of fuels: raw coals, petcoke, and biomass. This project supports the European strategy for accelerating the deployment of CCS for combating climate change, as committed by the EU and its member states.

Table II summarizes the main features of the Compostilla Project.

This technology will be initially tested on a first–of-its-class 30 MW_{th} boiler at es.CO_2, located in Cubillos de Sil (León), close to ENDESA's Compostilla Power Station in the northwest of Spain. The facility will provide the knowledge needed to further scale the technology to demonstration size (330 MW_e), once a positive final investment decision is made.

The Compostilla EEPR Project is led by a well-balanced consortium of ENDESA, CIUDEN, and Foster Wheeler. All three consortium members are dedicated and committed to the technology development and promoting the final project stage in order to achieve the successful commercialization of this promising CCS technology.

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References

1. Pikkarainen, T., Leino, T., Tourunen, A., and Kuivalainen, R. Development of CFB technology to provide flexible air/oxy operation for a power lant with CCS. *The 34th International Technical Conference on Clean Coal & Fuel Systems - Clearwater Clean Coal Conference*, Tampa, FL, 31 May–4 June 2009.
2. Eriksson, T., Nuortimo, K., Hotta, A., Myöhänen, K., Hyppänen, T., and Pikkarainen, T. Near zero CO_2 emissions in coal firing with oxyfuel CFB boiler. *9th International Conference on Circulating Fluidized Beds*, Hamburg, Germany, 13–16 May 2008.
3. Jantti, T. and Parkkonen, R. Lagisza 460MW_e supercritical CFB - operation experience during first year after start of commercial operation. *Russia Power Conference and Exhibition*, Moscow, Russian Federation, 24–26 March 2010.
4. Eriksson, T., Sippu, O., Hotta, A., Fan, Z., Ruiz, J.A., Sacristán, A.S-B., Jubitero, J.M., Ballesteros, J.C, Shah, M., Prosser, N., Haley, J., and Giudici, R. Development of Flexi-BurnTM CFB Technology aiming at fully integrated CCS demonstration. *Power-Gen Europe 2009*, Cologne, Germany, May 26-28 2009.
5. Cortes, V.J. State of development and results of oxy-coal combustion research initiative by CIEMAT in Spain. *2nd IEAGHG International Oxy-Combustion Network Meeting*, Windsor, USA, January 2007.
6. Cortes, V.J. CIUDEN´s Technology Development Centre for CO_2 Capture. *CCT2011 Conference*, Zaragoza, Spain, May 2011.
7. Lupion, M., Navarrete, B., Otero, P., and Cortes, V.J. CIUDEN CCS technological development plant on oxycombustion in coal power generation, Cottbus, Germany, September 2009.
8. Lupion, M., Navarrete, B., Otero, P., and Cortes, V.J. Experimental programme in CIUDEN's CO_2 capture technology development plant for power generation. *Chemical Engineering Research and Design*, vol. 89, no. 9, September 2011. pp. 1494–1500.
9. Lupion, M., Diego, R., Loubeau, L., and Navarrete, B. CIUDEN CCS Project: status of the CO_2 capture technology development plant in power generation. *10th International Conference on Greenhouse Gas Control Technologies, GHGT10*, Amsterdam, Netherlands, September 2010. ◆