OPTIONS OF CO_2 CAPTURE IN OXYFUEL COAL COMBUSTION TECHNOLOGIES

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A review of the projects that are developing the oxyfuel coal combustion technology around the world has been undertaken based on their available progress. The evaluation carried out is focused on different projects, such at small and large pilot scale as demonstration projects. All these studies and projects undertaken and in process show that fundamental understanding of the principles and basis of oxycoal combustion with flue gas recirculation have been well established during the past 20 years of R&D activities, but there are still some gaps in knowledge that are trying to be solved. The last objective of all of these projects is to demonstrate the oxyfuel technology in a commercial scale, taking into account another competitive alternatives, such the post-combustion for retroffiting existing power plants or the IGCC option. he conclusion of this study is that the oxyfuel combustion technology is suitable for retrofitting pf boilers and achieves clean coal combustion, lowering NOx, increasing SOx removal, possibly lower mercury emissions and obtaining a CO_2 concentration for sequestration.

Keywords: CO_2 capture, oxyfuel, coal, combustion

Introduction

Nowadays it is assumed by nearly everyone that the earth is warming. Since the moment that has been recorded the temperatures, by 1861, the earth's overall temperature has risen by 0.74 ºC. Other changing climatic parameters have been observed over recent years : heat-waves and periods of drought, flooding, glaciers melting, and a rise in sea level. In the opinion of the scientific community, climate change is very probably related to human activities and the large amounts of so-called greenhouse gases (GHG) that are accumulating in the atmosphere. The main GHG that causes the climate change is CO_2, which emissions to the atmosphere has been increased so rapid that it appears our planet is capable of absorbing only half of the emissions now generated by human activities.

This fact will provoke a disastrous impact on global warming, unless we reduce CO_2 emissions by 50%-80% by 2050, according to IPCC report.[1] Yet with world energy demand predicted to increase by 60% between 2004 and 2030, and renewable energies to make up only a third of the energy mix by 2050, the immensity of the challenge becomes clear and evident. Improving energy efficiency will help enormously, but in itself will not solve the problem.[2-3]

There are different possible alternatives that are taking into account in order to reduce the CO_2 emissions: improving energy efficiency, implementing renewable energies, changing lifestyle, increasing the use of biofuels and biomass, improving technologies for cleaner energy production from fossil fuels, etc. The last alternative cited is commonly called CCS (Carbon Capture and Storage) technologies, that represents a safe and efficient method of capturing and storing billions of tonnes of CO_2 underground for thousands of years. Furthermore, CCS involves three stages: capture, transport and storage. CO_2 is captured at a large, fixed source then concentrated and transported to a suitable storage site. For each of these stages, various techniques are either already available or being evaluated. Among the capture techniques, there's the capture by oxyfuel combustion, which involves combustion of the fossil fuel in pure oxygen rather than air so that the flue gas stream has a very high CO_2 content, 90% or even 95%.

This paper aims to show the actual situation of the worldwide projects that are trying to demonstrate the oxyfuel technology using coal as the fuel, making a discussion among them and focusing on its main characteristics.

Pilot Scale Projects

Pilot-scale studies on oxyfuel have used standard pf test facilities with additions of oxygen supply, capability to recycle flue gas, and possibly CO_2 compression capability. These typically have thermal inputs from 0.02 to 30 MWt and include those of EERC/ANL, IFRF, IHI, CANMET, AIR LIQUIDE, ENCAP and E.ON UK.

The earliest study of coal oxy-fuel combustion in a pilot-scale furnace was carried out by the Energy and Environmental Research Corporation (EERC) for Argonne National Laboratory (ANL) in their 3 MWt pilot facility located in the USA to test performance. The focus of the study is to demonstrate the technical feasibility of the CO_2 recycle into the boiler, to determine the ratio of recycle gas to O_2 for achieving heat transfer performance similar to air firing, to quantify the observable operational changes such as flame stability, pollution emissions, and burnout and to provide a basis for scaling experimental results to commercial scale.[4]

The main achievements of the study are that the oxyfuel combustion had a similar in-furnace gas temperature profile as the normal air-fired combustion and also it was found that oxyfuel combustion had lower NOx (50%) and SOx emissions, and a high carbon burnout compared to air firing.

The International Flame Research Foundation (IFRF) Study was carried out at their 2.5 MWt Facility located in the Netherlands, and aims to evaluate the combustion of pulverised coal during oxy-fuel combustion for retrofitting existing pulverised coal fired boilers to maximise the CO_2 concentration in flue gas. Besides, tries to optimise oxy-fuel combustion conditions to yield similar radiative and convective heat transfer performance to air firing and to evaluate the impact of oxy-fuel combustion on furnace performance, including flame ignition and stability, heat transfer, combustion efficiency, pollutant emissions, compared to air operation. The furnace used has internal square cross-section of 2x2 m and 6.25 m long air-staged swirl burner.[4] The results of the tests were similar to those from ANL/EERC tests, with the additional conclusions that the recycle ratio depended on the coal used and air leakage resulted in max CO_2 concentration to 91%.

The IHI Study was carried out at their IHI's 1.2 MWt Facility located in Japan. The combustion-test furnace has a horizontal cylinder furnace with 1.3 m inner diameter and 7.5 m length and a swirl burner. The focus of the study was to test the combustion characteristics of pulverised during oxyfuel combustion with primary consideration to reduce NOx and SOx pf boiler. The conclusions were that oxygen concentration should be high to raise the adiabatic flame temperature during oxy-fuel combustion to match that in air combustion and that the NOx and SOx emissions decreased.[4]

The CANMET Study is being performed by the Energy Technology Center, that is a division of Natural Resources Canada, in their Vertical Combustor Research Facility (VCRF) in Canada. This facility, which was built in 1994, has a long history in experimental results and represents CANMET's most modern pilot facility for combustion research. The facility has got a nominal thermal input of 0.3 MWt and is capable of firing pulverized coal and or natural gas using air or oxygen. The furnace is a cylindrical, down-fired and adiabatic vertical combustor with an inner diameter of 0.60 m and a length of 6.7 m. It is one of the few research facilities operating in the world that can fire pulverized coal in a mixture of recycled flue gases and oxygen in order to simulate O_2/CO_2 combustion techniques. These combustion techniques can be used to enrich the concentration of CO_2 in the products of combustion of fossil-fueled power plants in order to facilitate the capture of CO_2 for use and or sequestration. Furthermore, the objectives are to understand pulverised coal combustions behaviours in various O_2/FGR mixtures, compared with air combustion and to demonstrate the technical factors on the combustion performance. The tests proved the technical feasibility of the technology and the effect of oxygen purity recycle and different oxygen concentration in burner was also investigated. Besides, the emissions of NOx and SOx were lower (decrease in SOx by higher retention in ash).[4]

The Air Liquide and Babcock&Wilcox Study, with the sponsorship of the U.S. Department of Energy, was carried out at their facility of 1.5 MWt boiler with air staged combustion system located in the USA. The focus of the study is to demonstrate the technical feasibility of conversion from air firing to oxy-fuel combustion for large scale boiler and to highlight the impacts of oxy-fuel combustion process on pollutant (NOx, SO_2 and Hg) emissions and boiler efficiency. The results were that overall oxy-coal combustion characteristics were comparable to the air-firing case even with the change in oxidant composition from air to oxygen-enriched flue gas; the NOx emissions from oxy-coal combustion were significantly lower (65% less) than the air-fired case; the thermodynamics and heat transfer in the furnace and the convection pass changed only modestly; substitution of combustion air with oxygen and recycled flue gas increased the CO_2 concentration from 15% to 80% at the boiler exit; and the flue gas volume exiting the boiler is reduced by 70% relative to air-fired operation.[5]

The ENCAP Project is being developed in the context of an European project. The “Enhanced Capture of CO_2” (ENCAP) is a five-year integrated project (IP) within the EU sixth framework research programme.[6] This Project is structured in 6 Sub-Projects, and ENCAP SP3 is focused on oxyfuel technologies where combustion using almost pure oxygen and recycle of flue gas to moderate the combustion temperature is carried out.[8] In general the oxyfuel process used for power generation of large scale coal fired boilers is a new technique. Furthermore, the work in ENCAP SP3 is only related to oxyfuel combustion of solid fuel such as bituminous and lignite coal and pet coke and it's focused on PF and CFB technology. The goal of the work in ENCAP SP3 is to show that oxyfuel combustion of bituminous coal, lignite can reach a CO_2 avoidance cost of 20 € per ton of CO_2 by applying innovative design and utilise process integration opportunities. The objectives are to develop and validate oxyfuel combustion based power plants concepts for bituminous coal and lignite for a greenfield plant using PF and CFB boiler technology, to provide a conceptual boiler design and suggest its integration with a power generating plant to provide an economically competitive technology, and to examine special issues related to oxyfuel combustion in laboratory and pilot scale to be able to accommodate for those in the plant design and mitigate risk.

There are several work packages (WP) within this sub-project.

The WP 3.1 aims to understand the fundamentals in oxyfuel combustion that has been throughout the extensive experimental work performed in the 0.1 MWt gas-fired test unit of Chalmers and in the 0.02 MWt coal-fired unit of IVD at the University of Stuttgart.

The WP 3.3 and WP 3.4 aims to define the conceptual design of greenfield oxyfuel PF and CFB plant respectively, based on advanced supercritical power plant.

The WP 3.5 aims to perform combustion tests in semi-technical scale (0.5 MWt).

The WP 3.6 aims to validate the technology of oxyfuel in Vattenfall's 30 MWt oxyfuel pilot plant in Schwarze Pumpe.

In summary, a number of activities related to experimental investigations of oxyfuel fundamentals in the small-scale test rigs and the conceptual development of the full-scale oxyfuel PF and CFB plants have been finished. Combustion tests related to investigation of NOx emission behaviour with staged combustion under simulated oxyfuel conditions have been investigated. Similar reduction behaviour as under air firing has been concluded. The investigated ash and slagging behaviour under oxyfuel and air firing conditions with ENCAP coals have also found to be similar. In the work package related to conceptual design of oxyfuel PF plants, and economic assessment including transport and storage scenarios has been concluded. The layout of the system used for compression and processing of CO_2 has been reported together with identification of processes to be included to reach the CO_2 purity levels defined for the Enhanced Oil Recovery (EOR) and ship transport case in the ENCAP guidelines. A RAM analysis has been performed. The conceptual design of the oxyfuel CFB plant has been finished. Activities to reconstruct a 0.5 MWt test rig at the University of Stuttgart for oxyfuel operation has mainly been finished and the functionality of the rig demonstrated. A decision to focus the ENCAP Phase II Large Scale Testing activities on tests in Vattenfall 30 MWt Oxyfuel PF Pilot Plant in Schwarze Pumpe power station in Germany has been taken.[7]

In short, the main achievements and conclusions of ENCAP SP3 are, after analysing the combustion characteristics of oxyfuel combustion of 2 lignites and 2 bituminous coals in small combustion facilities (0.02-0.5 MWt), for PF plant, to achieve similar temperature profile as in air-firing requires higher overall O_2-level (25-27%(v)) but will result in higher gas radiation intensity; for CFB tests have been performed up to 90%(v) O_2 in oxidant; NOx reduction is possible through flue gas recycle and staged combustion; no major impact on burnout and CO level at furnace outlet and no major impact on composition of ash and deposits detected. With regard to the oxyfuel power plant concept development, we can conclude that the conceptual designs of PF and CFB oxyfuel plants have been established (1st generation oxyfuel plants) with the characteristics that the design for the furnace and boiler is more compact than for air, the design of a CO_2 compression and purification unit to reach the required <4% non-condensable components in CO_2 product, the economic analysis indicate that the target of 20 €/ton CO_2 avoided (year 2004 level) can possibly be reached for a n^{th} plant, the procedures for start-up and shut-down and load change have been suggested, the safety aspects, technical risks and resulting expected availability for a n^{th} oxyfuel plant and no show-stoppers have been identified.[8]

The E.ON UK Study is carried out at their Facility located in the UK and property of E.ON Company. This study is being developed under a Project called “Assessment of Options for CO_2 Capture and Geological Sequestration (ASSOCOGS)” which is looking for ways of capturing CO_2 produced from oxyfuel combustion plants with advanced supercritical boiler and turbine technology. It’s a project in association with the Research Fund for Coal and Steel (RFCS) and the work package which is related to the oxyfuel technology is WP2 “Oxyfuel combustion”. The Combustion Test Facility (CTF) is already demonstrating oxyfuel firing technology and besides E.ON is collaborating with other industrial partners to demonstrate large-scale oxyfuel burners. The objectives of the WP2 are to review design of CTF for oxyfuel combustion, to develop revised operational procedures, to prepare detailed redesign, to construct and commission CTF, to refine operational procedures, to perform parametric testing and to review findings and implications.[9]

The E.ON UK’s 1 MWt CTF was commissioned in 1993, has got a time-temperature scaled and it can operates with varieties of fuel: coal, biomass, oil, orimulsion, gas, others. Besides, has got a full combustion staging (overfire air, reburn and flue gas recycle) and is highly instrumented and controllable. The thermal input is 1 MWt (0.8 – 1.2 MWt), the furnace is horizontally fired, refractory lined, water cooled and balanced draft, with dimensions of 1m x 1m x 1m.[10] The conclusion of the tests carried out demonstrated a stable flame without burner O_2 addition, some reduction in NOx concentrations, similar composition of the deposits and the ashes.

Table 1 provides a summary of the studies about oxyfuel technology performed at a laboratory scale and at a small pilot-scale that have been explained previously.

Large Scale Pilot and Demo Projects

Large Pilot-scale and Demo Projects studies on oxyfuel that have used standard pf test facilities with additions of oxygen supply, capability to recycle flue gas, and possibly CO_2 compression capability. These typically have thermal inputs from 30 MWt and include those of Jupiter, Ciuden, B&W, Vattenfall, OxyCoal-UK, Callide, Jamestown, Pearl Plant and Youngdong.

The US Coal Jupiter Oxyfuel Project is carried out at a Facility of 15 MWt in Indiana (USA) by the Jupiter Oxygen Corporation, who has patented fossil fuel combustion technology using a high temperature flame with 95% to 100% pure oxygen for combustion while air is excluded. Therefore, there is no airborne nitrogen. Nitrogen uses energy during combustion, thereby reducing the amount of energy available to be transferred to the water tubes for the making of steam. Lower nitrogen means that more combustion energy is available for making steam. The oxy-coal flame is at a much higher temperature and generates far more radiant energy transfer than an air-coal flame (also true using other fuels). Radiant heat transfer is far more efficient than convective heat transfer (the higher flame temperature can be safely used for power plant retrofits with existing materials and existing process temperatures). Furthermore, Jupiter's combustion technology operates at or very close to stoichiometry and creates longer residence times. This means that there is a more efficient burn of the fuel and more time for the energy generated to be absorbed as the heated gas passes through the boiler. These four factors (reduction of nitrogen at combustion, greater radiant heat transfer, stoichiometric oxygen-fossil fuel ratio and longer residence times) mean that Jupiter Oxygen's technology makes boiler combustion become much more efficient and use significantly less fuel to create the desired megawatts. In addition, exit gas emission clean-up with back-end technologies are more efficient and less costly because of lowered NOx at combustion with air excluded, lower pollutants due to the fuel reduction, reduced exit gas volumes and the changed composition of the exit gases. The Jupiter Oxygen patented technology also results in more concentrated CO_2, resulting in less expense capture and sequestration. Initial test results using carbon and natural gas showed a tenfold increase in CO_2 concentration.[11]

The CIUDEN Spanish Project consists in the development of the oxyfuel technology by means of the construction of a Test Facility with pulverised coal technologies (20 MWt) and coal fluidised bed technologies (20 MWt). Some of the technical characteristics of the Experimental Facility are that it has got a Pilot PC boiler with 2+2 burners in order to see the flame interactions. Besides, it has a flue gas cleaning section for NOx, SOx and particles and a CO_2 Capture Section, including several technologies, such as chemical absorption (amines), flue gas compression and carbonation/calcination eventually. The initial focus is low volatile fuels (anthracites and petroleum coke), which is a differential factor as regards to the other international projects. It has fully integrated preheating train adaptable to any operating scenario, from air-fuel to oxyfuel combustion.[12]

The B&W Clean Environment Development Facility (CEDF) for CO_2 capture Project is carried out in Alliance, Ohio (USA) and was managed and funded by Babcock&Wilcox, American Liquide and Utility Advisory Group. The CEDF was modified to use and mix oxygen, added WFGD and other auxiliary equipment for oxycoal and the boiler type is pulverised coal. The Utility Advisory Group provided end user design feedback for commercial applications. The test campaigns underway include lignite, sub-bituminous coal and bituminous coal. The plant was built in 1994 with support of DOE and others, and it's in operation since 2007. The input of coal is 30 MWt. The results of the tests proved that the emissions of NOx were significantly reduced (>50%), the SO_2 removal was not significantly different than with air and the oxy flame was bright and stable.[13]

The German Vattenfall Project is cited above, within the last stage of the ENCAP Project, and is carried out by Vattenfall, who has taken a decision to build a 30 MWt

Oxyfuel PF pilot plant near to the existing power plant at Schwarze Pumpe. The investment decision was assumed in May 2005, and it's in operation since August 2008. Pilot testing using lignite will result in validation and tuning of the more or less commercially available technologies included in the oxyfuel concept to allow launch of a demonstration project of the technology in commercial scale by 2015 (≈ 600 MWt). The objectives of these tests are to define optimal operating technologies for oxyfuel conditions in a large-scale facility for the entire process, to identify critical issues for further R&D and to gain operating experience in the oxyfuel field.[14]

The OxyCoal-Uk Project consists in developing and demonstrating a competitive oxyfuel firing technology suitable for full plant application post-2010. To reach this goal, the Project is structured in three stages. The phase 1 aims to understand the fundamentals and underpinning technologies, the phase 2 aims to demonstrate an Oxyfuel Combustion System of a type and size (40 MWt) applicable to new build and retrofit advanced supercritical oxyfuel plant and the last stage completes, thanks to the previous stages, the foundation for the development of an oxyfuel boiler reference design, demonstration plant installation and operation.[15]

The Callide Oxyfuel Project is a project performed by Australia and Japan and consists in retrofitting 30 MWe (90 MWt) oxyfuel coal-fired power plant for capture and storage demonstration. The Callide Oxyfuel Project will take the technology to a larger scale in order to demonstrate that it can be applied to existing and new coal-fired power stations to achieve very significant reductions (up to 90% of CO_2) in emissions.[16] The objectives of this Project are to establish the design and operating requirements for large scale (commercial) retrofit and new-build oxyfuel plants, including geological storage and to estimate capital and operating costs for the next generation of oxyfuel near zero emission technology electricity generating plants.[17]

The Jamestown Oxy-Coal Demonstration Project is a demonstration-scale 50 MWe oxy-fuel coal plant with CCS and is located in Jamestown, New York (USA) and carried out by the New York Oxy-Coal Alliance and other companies, Praxair among them. The Oxy-Coal Alliance also provides the opportunity to explore geologic carbon sequestration and a new carbon capture technology ("oxy-fuel," developed by New York-based Praxair). The objectives of the Project are to demonstrate the fully integrated CCS project, to employ advanced technologies (CFB boiler, ASU and CO_2 processing unit and system integration), to prove reliability and availability, to operate with typical load factor variations and to learn transient modes of operations. These goals will enable direct scale-up to a commercial CCS operation. The project is estimated to start up in 2013.[18]

The Pearl Plant Project is carried out in a Facility with has a 22 MWe (66 MWt) PC boiler and is located in the USA. The main fuel is bituminous coal and it's estimated to start up in 2009.

The Youngdong 100 MWe (300 MWt) Oxy-Combustion Power Station Project Demonstration is carried out by the Korea Electric Power Research Institute, with the support of the Korea Institute of Science and Technology and is located in Youngdong (Korea). The Project aims to replace the Youngdong 125 MWe unit #1 that is currently being operated with domestic anthracite and it will be decommissioned by 2013. The objectives of the Project are to demonstrate the oxy-fuel operation by 2018, to improve the fuel flexibility, using sub-bituminous coal, and to optimize the power generation cost.[19]

Table 2 provides a summary of the different large scale pilot and demo projects developing the oxy-coal technology.

Figure 1 shows the oxy-coal combustion projects in operation and planned to start up in the world-scene.

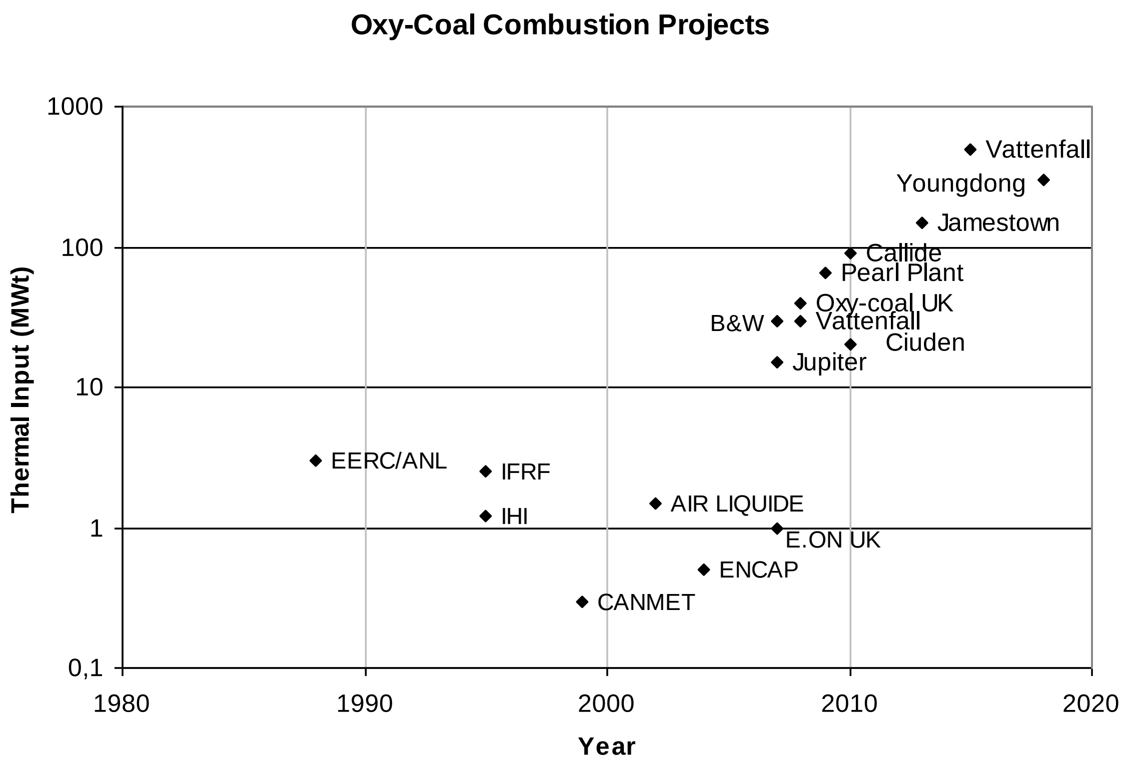

Figure 1. Oxy-coal combustion projects in operation and planned to start up in the world-scene.

Discussion

It's obvious the rising importance that the oxy-combustion is acquiring in the context of the climate change as a potential greenhouse gas (GHG) mitigation option for fossil fuel power plants. Proof of this, is the number of projects that have been doing up to now and those in progress.

After initial introduction in the early 80's, oxyfuel combustion for pulverised coal combustion was researched as a means to produce relatively pure CO_2 for Enhanced Oil Recovery (EOR). Despite these research efforts, the technology did not pick up on a large scale for this application. However, the awareness and the concern for the greenhouse gas emissions into the atmosphere has taken up the interest again in this technology, with a two-fold focus: the generation of a concentrated stream of CO_2, which is need for sequestration, and the potential to reduce pollutant emissions, in particular NOx. This research into this technological option for capturing CO_2 has not been limited to the construction and development of new plants that have the advantage of smaller flue gas cleaning equipment due to the lower volume, but has also included the retrofiting of current plants that are in operation.

This renewed interest in oxyfuel combustion has impulsed to many laboratory-scale and small and large pilot-scale studies to develop and demonstrate this technology. The main technical considerations and key points in the development of oxy-coal combustion with CCS are: the combustion section (furnace/boiler), the flue gas cleaning section, the CO_2 capture section and the O_2 supply section. The issues that need further investigations detail to obtain a more fundamental understanding of the changes between oxyfuel combustion and conventional air-fired combustion are: heat transfer performance of new and retrofitted plant and the impact of oxygen feed concentration and CO_2 recycle ratio; the gas cleaning required; assessment of retrofits for electricity cost and cost of CO_2 avoided; the combustion of coal in an O_2/CO_2 atmosphere, including ignition, burn-out, and emissions.

Regarding the boiler, most of them are pulverised coal (PC) boilers. The advantages of the circulating fluidized bed (CFB) regarding the PC boilers are that in an oxygen-fired CFB system, with the proper amount of recirculated gas, it is possible to obtain bed conditions within the furnace that are very similar to air firing using the appropriate systems that can be designed to have the same flue gas flow to coal flow ratio as with air firing and the same volumetric fraction of oxygen in the flue gas leaving the bed as that of the air-fired case. Furthermore, a critical advantage for oxygen-fired CFB type furnaces is the capability to reduce flue gas flow for a given coal input, by minimizing the recirculated flue gas flow, while maintaining the furnace temperature. With an oxygen-fired CFB, a recycling loop of solid materials is used, by adjusting the heat pick up, to control the furnace temperature at an optimum operation level for combustion efficiency without any potential risk of agglomeration. The concept scheme offers significant opportunities for size and cost reduction in greenfield design. Moreover, due to the inherent fuel flexibility associated with the CFB boiler, multiple fuels can be used such as coal, petroleum coke, biomass and a range of opportunity fuels.[20]

From the studies done so far, a list with the main advantages and disadvantages regarding the oxyfuel technology extracted are shown in Table 3.

Conclusions

All these projects explained in this review show the rising importance of the oxyfuel technology as a technological option to capture CO_2.

The pilot-scale studies have demonstrated the feasibility of pulverised coal oxy-fuel combustion. Besides, no major technical barriers in pilot-scale studies have been found and furthermore, the oxyfuel combustion technology is suitable for retrofitting pf boilers and achieves clean coal combustion, lowering NOx, increasing SOx removal, possibly lower mercury emissions and obtaining a CO_2 concentration suitable for its sequestration.

Technology has been demonstrated only at a laboratory and pilot-scale, not at a practical scale, but demonstrations are planned. The ability to capture CO_2 from power plants is feasible in advanced modes of current technology and with new technologies under development with significant industry-driven R&D underway.

Oxy-combustion technology requires introducing some new equipment such as the ASU and the CO_2 CPU to power plants. Furthermore, new coal fired power plants shall be designed for highest efficiency to minimize CO_2 and other emissions. Oxy-combustion is complementary with conventional boiler and steam power plant technology, including efforts towards ultra-supercritical conditions (for efficiency), and environmental control developments. Therefore, to demonstrate this technology, is needed performance optimization (management of incondensibles like Ar, N_2 or O_2, combustion with low NOx and excess O_2, boiler start up and optimization); CO_2 treatment (purification, compression and utilization of the captured CO_2); optimize the power generation cost (minimize the efficiency penalty, CO_2 capture cost), and scale-up and validation.

The opportunities of the deployment of oxy-combustion technology are due to the low technological risk option, it's possible a large power plant size and the repowering and retrofitting, all boiler technologies are adaptable with the use of flexible fuels, the increase of the steam cycle is also possible, apart from the potential reduction of the size of the boiler ant the supply of advanced O_2.

The challenges that has to face this technology are those related to the time (on time development), technology (scale-up validation, adaptation to installed base, innovation), regulatory policy (air and CO_2 injection permits), government budget to support CCS demonstration and value for CO_2. Besides, another important challenges are the cost (cryogenic oxygen, CO_2 quality, CO_2 compression, heat flow optimisation, integration) and the public acceptance of this technology. Particularly, the challenges that have to face the demonstration projects are that all pilot projects will proceed with industrial and governmental financial support.

The success factors for the demonstration of this technological option are those engaged with financial, regulatory, legal, geological and technical issues. It's also important for the final result the proximity to a suitable geologic CO_2 storage site and the receptivity by stakeholders.

The possible future uncertainties for the sucess of this technology are mainly, the international CCS regulations and weak storage resources.

Work to date has demonstrated oxyfuel technology as a technically viable solution for CO_2 Capture that combines well proven, commercially available components with minimal risk.

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Table 1. Studies about Oxyfuel Technology performed at a Laboratory Scale and at a Small Pilot-Scale

organism	MWt Facility	location	focus of the study	results compared to air-fired combustion
EERC/ANL	3	USA	CO_2 recycle boiler determine ratio FGR	similar temperature profiles lower NOx, SOx emissions

			quantify operational changes provide a basis for scaling	high carbon burnout higher CO_2 concentration
IFRF	2.5	Holland	retrofitting of existing pc optimise combustion conditions evaluate furnace performance	similar temperature profiles lower NOx, SOx emissions high carbon burnout FGR depends on coal and air leakage higher CO_2 concentration
IHI	1.2	Japan	reduce NOx and SOx pf boiler	same heat flux lower NOx, SOx emissions higher CO_2 concentration
CANMET	0.3	Canada	pc combustion in O_2/FGR mixtures combustion performance	lower NOx emissions lower SOx by higher retention in ash higher CO_2 concentration
AIR LIQUIDE	1.5	USA	retrofitting from air-fired to oxyfuel evaluate emissions NOx, SO_2, Hg determine boiler efficiency	lower NOx emissions (65% less) similar temperature profiles similar thermodynamics higher CO_2 concentration
ENCAP	0.5	UE	fundamentals of oxyfuel	higher [O_2] to achieve similar

			combustion evaluate oxyfuel issues at lab scale develop oxyfuel PF and CFB boiler provide conceptual boiler designs	temp profiles for PF lower NOx emissions similar carbon burnout similar ash and deposit composition similar CO levels boiler and furnace is more compact higher CO_2 concentration
E.ON UK	1	UK	demonstrate oxyfuel technology	stable flame without burner O_2 addition similar ash and deposit composition lower NOx emissions

Table 2. Different Large Scale Pilot and Demo Projects developing the Oxyfuel Technology

project	MWt	location	start up	boiler type	main fuel
Jupiter	15	USA	2007	industrial	natural gas
					coal
Ciuden	20+20	Spain	2010	pilot PC + pilot CFB	anthracite
					petroleum coke
B&W	30	USA	2007	pilot PC	bituminous coal
					sub-bituminous coal
					lignite
Vattenfall	30	Germany	2008	pilot PC	lignite
Oxy-coal UK	40	UK	2008	pilot PC	coal
Pearl Plant	66	USA	2009	pilot PC	bituminous coal
Callide	90	Australia	2010	pilot PC	bituminous coal
Jamestown	150	USA	2013	pilot CFB	bituminous coal
Youngdong	300	Korea	2018	100 MWe PC	coal
Vattenfall	600	Germany	2015	200 MWe PC	lignite
					bituminous coal

Table 3. Main advantages and disadvantages of the oxyfuel technology

advantages	disadvantages

operation similar to air-fired boiler, high availability	significantly reduced efficiency because of ASU and CO_2 compression, by 9%
ability to operate in oxygen or air mode.	reduced sent out electricity by 18-20%
applicable for existing (retrofitting) and new PF plants and CFB plants	may require SOx removal
lower emissions of SOx, NOx, Hg	large air separation unit is required compared to other near-zero technologies
flue gas volume lower than air-fired combustion	not applicable to capture-ready plants
variety of feedstocks can be used	
does not require CO_2 capture prior to compression	