Developments in circulating fluidised bed combustion

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Abstract

While pulverised coal combustion (PCC) remains the dominant technology in the power generation sector, a significant minority of plant commissioned is based on circulating fluidised bed combustion (CFBC). CFBC offers specific advantages over PCC, particularly in the utilisation of low quality coals, and mixtures of coal with other fuels, including wastes. Since its initial deployment, CFBC has continued to evolve. Recently, significant advances have been made in scaling-up the CFBC units and in the adoption of supercritical steam parameters. The engineering designs and operation of the CFBC systems have also been optimised leading to improvements in plant reliability and availability, and plant economics. The CFBC technology is emerging as a real competitor to PCC system.

For PCC and CFBC boilers, oxy-fuel combustion systems that produce high purity CO_2 exhaust streams ready for carbon capture are under development. Oxy-CFB technology may have some advantages over oxy-PC combustion designs but there are challenges in the development of the concept and design of oxy-CFB boilers. This report reviews the recent developments in CFBC technology and how it fits within carbon capture and storage strategies.

Acronyms and abbreviations

AFT	adiabatic flame temperature
CCS	carbon capture and storage
CFBC	circulating fluidised bed combustion
CIUDEN	Fundación Ciudad de la Energía
cm	centimetre
COE	cost of electricity
CPU	carbon purification and compression unit
EHE	external heat exchangers
EU	European Union
FBC	fluidised bed combustion
FBHE	fluidised bed heat exchanger
FW	Foster Wheeler
HHV	high heating value
IEA CCC	International Energy Agency The Clean Coal Centre
km	kilometre
$kg/m^2.s$	kilograms per square metre per second
kW	kilowatt
LHV	low heating value
mm	millimetre
MPa	mega pascal
MWe	megawatt electric
MWh	megawatt hour
MWth	megawatt thermal
NETL	The National Energy Technology Laboratory, USA
PC	pulverised coal
PCC	pulverised coal combustion
R&D	research and development
TDC	Technology Development Centre
t/h	tonnes per hour
US DOE	US Department of Energy
VOC	volatile organic compounds
vol%	percentage by volume
VTT	Technical Research Centre of Finland
WDF	waste derived fuel

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1 Introduction

Fossil fuels will remain the primary energy source for electric power generation for the foreseeable future, and coal is the principal fossil fuel of power generation. Coal can be expected to remain an essential energy source well into the 21st century and even in the 22nd century due to its low cost and broad availability. However, given that coal-fired power plants represent one of the largest producers of CO_2 emissions, it is prudent public policy to aim at the development and early application of clean technologies for coal utilisation in high efficiency power cycles. The power industry has progressively improved power plant designs to meet increasingly stringent limits for air pollution. New coal plants today are cleaner and more efficient than plants built in the past. This report reviews the recent advances in circulating fluidised bed combustion (CFBC) technology for power generation including the development of oxy-CFB technology with carbon capture and storage (CCS).

CFBC, as an alternative to pulverised coal combustion (PCC), uses a fluidised bed, an apparatus that mixes coal and air with a sorbent such as limestone during the combustion process, to facilitate more effective chemical reactions and heat transfer. In a fluidised-bed combustor, combustion occurs when the mixture of fuel, a sorbent and fuel ash particles is suspended by using a continuous stream of primary combustion air to create turbulence in the bed. The gas cushion between the solids allows the particles to move freely, giving the bed a liquid-like (fluidised) characteristic. CFBC technology offers several benefits. CFBC boilers are extremely flexible, allowing a wide range of fuel qualities and sizes to be burnt. Emissions of SOx and NOx are significantly reduced without the addition of expensive flue gas emissions control systems. This is due to the fact that the combustion temperature in a CFBC boiler (800–900ºC) is significantly lower than in a PCC boiler (1300–1700ºC), which results in considerably reduced NOx formation compared to PCC. The majority of the sulphur in the coal is captured by limestone that is injected into the furnace; about 90% to 95% SO_2 reduction can be achieved. The lower combustion temperature also limits ash fouling and corrosion of heat transfer surfaces allowing the CFBC to handle fuels that are difficult to burn in a PCC boiler. Even though the combustion temperature of a CFBC boiler is low, the circulation of hot particles provides efficient heat transfer to the furnace walls and allows a longer residence time for combustion and limestone reaction. This results in good combustion efficiencies, comparable to PCC boilers. One of the disadvantages of the technology is that NOx and SOx emissions may exceed current stringent standards in some areas when the boilers are operated at less than full load. Further, the nature and impacts of CFBC residues (primarily ash) are not fully understood and therefore their disposal requires careful consideration.

CFBC technology is well suited to burn low grade and/or difficult to burn fuels. Many existing CFBC units are fired with waste coal and serve to clean up waste piles left over from mining activities, turning low/zero waste coal to valuable electricity. CFBC technology has been employed for power generation for over 25 years and the technology is still evolving. Almost all of the existing CFBC power generating units are small in size (≤330 MWe compared to >1000 MWe for a PCC boiler), and use subcritical steam conditions that makes CFBC systems less efficient than supercritical/ultra-supercritical PCC plants. The poorer economy of scale and lower efficiency of the CFBC plants result in higher plant costs and has limited its deployment.

Over the last decade, significant advances have been made in scaling-up CFBC units and in the adoption of supercritical (SC) steam cycles. In 2009, the first supercritical and the largest hard coal fired 460 MWe CFBC power generating unit was successfully commissioned in Łagisza, Poland. More coal-fired SC CFBC power plants with unit sizes of 550 and 600 MWe are under construction in South Korea and China. Today, SC CFBC boilers with capacities up to 800 MWe are commercially available. In addition to the increase in size and the use of advanced steam cycles, the engineering designs and operation of the CFBC systems have also been optimised leading to improvements in plant reliability and availability, and plant economics. The CFBC technology is emerging as a real competitor to PCC system.

The major challenge facing the power generation industry over the coming decades will be to increase the efficiencies of fossil-fuelled power plants while meeting increasingly stringent environmental goals. In particular, there is a need to reduce the emissions of CO_2 to the atmosphere, with near-to-zero CO_2 emissions being the ultimate goal. Intensive research and development (R&D) is ongoing to develop and commercialise technologies for carbon capture and storage (CCS). For PCC and CFBC boilers, oxy-fuel combustion systems that produce high purity CO_2 exhaust streams ready for carbon capture are under development. Oxy-fuel combustion is based on existing boiler technologies with addition of compression and separation processes that already exist in other industries and that have only to be adapted and scaled-up to power generation application. Oxy-CFB technology may have some advantages over oxy-PC combustion designs. When oxy-fuel combustion is applied to a CFBC boiler, the combustion temperature can be controlled by recycling a portion of the cooled solids to the furnace through a fluidised-bed heat exchanger, therefore minimal flue gas recirculation is required. This characteristic allows the oxy-CFB boiler to be made smaller and less expensive in a new unit application.

A power generation technology based on oxy-CFB with CO_2 capture will provide typical benefits of CFBC boilers, in particular the fuel flexibility. The ability to fire low grade coals or cofire waste fuels reduce dependence on expensive high rank imported coal, and thus reduces the cost of electricity. In addition, higher O_2 concentrations in the combustion gas are expected to increase combustion efficiency and will reduce the flue gas flow rates and thus increase the boiler efficiency. Smaller furnace volumes may reduce costs of the boiler island. Initial commercial designs will likely have dual capability to operate in either oxy-firing or air-firing mode. This will provide a high degree of flexibility and reduce risk to the plant owner from the implementation of the first of a kind oxygen-firing technology.

Oxy-CFB technology is developing rapidly, in particular with the commissioning in September 2011 of the first pilot scale oxy-CFB test facility at CIUDEN in Spain. A 300 MWe oxy-CFB plant in the adjacent Compostilla Power Station is also under consideration.

This report begins with an overview of the current status of the CFBC technology. A description of the CFBC process is given in Chapter 2, followed by an evaluation of its operational and environmental performances. The variations in designs by different suppliers and the applications of the CFBC technology are also reviewed. Chapter 3 looks at the recent developments in the CFBC technology. Technical advances and improvements in engineering designs in the main components of the CFBC system such as the furnace, the solid separation system and external heat exchangers are examined in detail. The recent developments in scaling-up and the utilisation of supercritical steam conditions are discussed. Other developments and optimisation such as improved design for co-combustion of biomass with coal in a CFBC boiler are also reflected in this chapter. The current R&D activities on developing oxy-fuel CFBC technology are presented in Chapter 4. The oxy-CFB combustion process and design challenges are analysed first, and then the developments in oxy-CFB technology are reviewed. The performance and economics of coal-fired power plants based on oxy-CFB technology are evaluated. A comparison of oxy-CFB and oxy-PC power plant is performed. Finally, conclusions are drawn in Chapter 5.

2 Current status of CFBC technology

Circulating fluidised bed combustion (CFBC) is the predominant type of FBC used for power generation. The first development work on CFBC began in Germany in the mid-1970s, which was followed by work in Sweden, Finland and the USA. The first use of the CFBC technology for power generation started in 1985 with the operation of a 90 MWe CFB boiler in Duisburg (Germany). Since then, almost 600 coal-based CFBC generating units with a total capacity of more than 46 GWe have been installed worldwide (Platts, 2012). Coal-fired power plants using CFBC technology have been operating in the USA, Europe and Japan since the 1980s, and can be found more recently in the emerging economies such as China. Today, CFBC technology can be considered as a mature technology for power generation/co-generation and industrial-sized applications and is commercially available from multiple suppliers.

2.1 Process description

Steam generators with CFBC have found a wide application worldwide for power generation over the past two decades. Figure 1 shows an example of a modern power plant using CFBC. Fuel and limestone are fed into the combustion chamber of the boiler while air (primary and secondary) is blown in to ‘fluidise’ the mixture. The fluidised mixture burns at a relatively low temperature and produces heat. The low combustion temperature limits the formation of NOx whilst the limestone absorbs SO_2 formed during the fuel combustion. Heat from the combustion process boils the water in the water tubes turning it into high-energy steam, which is used to drive a steam turbine for power generation. Ammonia can be injected into the boiler outlet to further reduce NOx emissions. A heavy-duty cyclone is used to separate the entrained ash and unburnt fuel particles from the flue gas and return them to the lower part of the combustor. This allows the particles to remain within the system for long enough to ensure both effective combustion of the carbon and maximum sulphur capture. The finest particles, however, are not recirculated and escape from the cyclone. The hot flue gas leaving the cyclone enters a convection pass which includes a superheater, an economiser, and, in

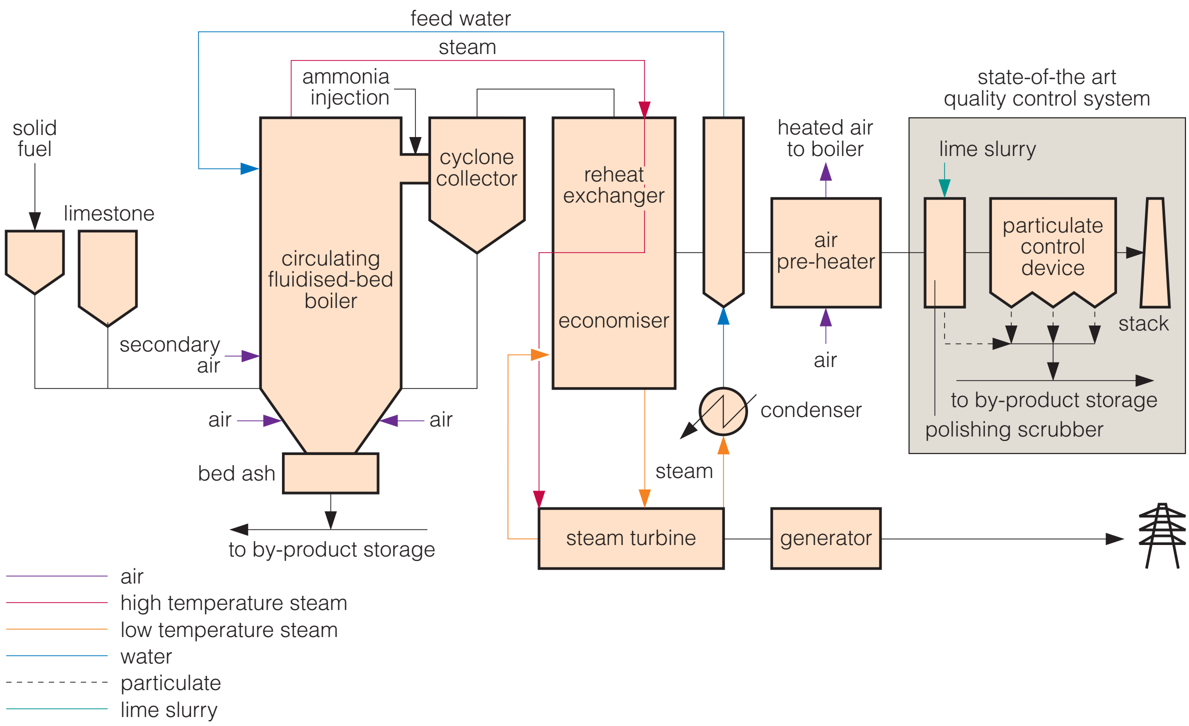


Figure 1 A CFBC power generation plant (UNEP, 2007)

some of the more recent installations, a reheater. In this section much of the remaining heat is extracted. The cooled gas passes through an air heater before entering a baghouse or electrostatic precipitators (ESP) for removal of fine particles and finally is discharged to a stack. More recently, a polishing dry scrubber is added downstream of the air heater and upstream of the dust control device to remove additional SO_2. This process allows the Ca/S ratio to the CFBC furnace to be reduced while still achieving overall SO_2 removal greater than 95%.

The controlling parameters in the CFBC process are temperature, residence time and turbulence. The combustion temperature of a CFBC boiler is in the range between 800ºC and 900ºC, which is significantly lower than a pulverised coal fired boiler (1300–1700ºC). The low combustion temperature results in a considerably reduced NOx formation in CFBC compared to pulverised coal combustion. CFBC employs high fluidisation velocities to promote the carryover or circulation of the solids. Solid separation systems are used to capture the unburnt solid fuel and bed material for return to the primary combustion chamber for more efficient fuel utilisation. In CFBC boilers, air staging is commonly used. Except in the lowest part of the boiler, with a bubbling bed region, the upward flow rate of air/combustion gases is typically 5–7 m/s. Boiler height varies depending on plant size, but is commonly in the range 12–30 metres. The residence time for air and combustion gas is accordingly between two and six seconds. For large units, the taller furnace characteristics of CFBC boilers offers better space utilisation, greater fuel particle and adsorbent residence time for efficient combustion and SO_2 capture, and easier application of staged combustion techniques for NOx control.

2.2 Main components

A CFBC unit generally features some or all of the following elements:

- A combustor in which solid fuel and absorbent are injected and are fluidised together with recycled solids by combustion air that is blown into the furnace. Primary air is introduced below the grid plate whilst additional combustion air is injected as secondary air above the grid plate.
- A solids separation system such as high efficiency cyclones is installed at the combustion chamber outlet in the high-temperature gases (~750ºC to 950ºC) to collect most of the solids leaving the chamber and return them to the combustor. The small fraction of the fly ash produced is carried by the discharged flue gas and removed downstream of the heat recovery system using particulate collectors such as ESPs and fabric filters.
- A convective pass that may contain superheaters, reheaters, economisers and air heaters, arranged in the same order in the gas flow direction. There are in-line and over-the-top designs for the convective backpass. The in-line design locates the backpass on the same side of the cyclone relative to the furnace. With the over-the-top design, the backpass is located on the opposite side of the cyclone relative to the furnace.
- Internal and external heat exchanger (EHE). EHEs are generally located downstream of the cyclones. The cyclones or other solids collection device may be cooled with steam or water in order to reduce wear of materials, and in this case steam or hot water is produced. Optional heat exchange surface can be provided in the form of a fluidised-bed heat exchanger (FBHE) into which the collected stream of solids from the flue gas is fed and where internal heat from the solids is transferred to water or steam. The distribution between hot solids and recycled cooled solids keeps the combustion chamber temperature at the desired value.

In addition, a CFBC boiler also comprises fuel and sorbent feeding systems, an air feeding/distribution system, and a bottom ash handling/extraction system. A fuel feeding system consists typically of 2–4 independent fuel feed lines, divided equally to front and rear walls of the furnace. One fuel feeding line generally includes a fuel silo, a fuel feeder, a fuel conveyor and discharge to the feeding points. Feeding points are located symmetrically to each furnace section to ensure uniform combustion in the furnace. Compared to fuel feeding, sorbent feeding is relatively easy and flexible. Sorbent can be fed pneumatically into the furnace through openings on the front wall, side wall, rear wall and/or loop seal. Alternatively, a mechanical feed system can be employed.

Air supply to the CFBC furnace is divided into primary and secondary air. The primary air (approximately 50% of the combustion air) is introduced through a nozzle grid in the floor to fluidise the bed material and for combustion in the lower furnace. Properly designed nozzles allow for good distribution of primary air to the furnace to create a reducing environment in the lower part of the combustion bed. The primary air flow through the air distributors/nozzles is measured and controlled separately to ensure equal air flow to all sections of the grid and uniform fluidisation, which leads to adequate mixing of air, fuel, sorbent, and ash in the primary loop resulting in optimal conditions for combustion and desulphurisation by preventing hot spots. The secondary air is introduced at elevations along the walls to provide staged combustion, thus reducing NOx formation and completing combustion. The number of secondary air injection levels and ports can vary with design but two or three injection levels are commonly adopted.

In CFBC boilers, the bottom ash constitutes roughly 30–40% of the total ash, the rest being fly ash. The bottom ash is removed by continuous overflow to maintain bed height and also by intermittent flow to remove oversize particles, avoiding accumulation and consequent defluidisation. The bottom ash extraction system can be either a fluidised bed ash cooler or a water-cooled screw cooler. The heat of the ash is recovered to improve the boiler efficiency (UNEP, 2007).

2.3 Status of the technology

Following the successful operation of the first commercial CFBC unit that started in 1979 in Finland, the number of installations has increased rapidly in the past decades. CFBC technology has found applications in many industrial processes and been employed for power generation for more than 20 years. There have been continuous innovations and advances in CFBC technology and it is still evolving.

2.3.1 Operational performance

A comparison of CFBC technology with pulverised coal combustion (PCC) technology was performed in a recent study (Zhu, 2012). The results from this work showed that CFBC technology is emerging as a strong competitor to PCC. Modern large SC CFB boilers have performance and economics comparable to corresponding PCC boilers while offering greater fuel flexibility, especially the ability to burn low heating value opportunity fuels.

Efficiencies

When talking about the efficiencies of fossil fuel-based power generating units, most often the thermal efficiency of a unit is addressed. Sometimes, however, combustion efficiency and boiler efficiency are also discussed. The combustion efficiency is the ability of a furnace to burn carbon. The combustion efficiency varies with the type of fuel used and it is typically higher for reactive fuels than for less reactive fuels. CFBC systems have an inherent advantage in that they are designed to increase solids residence times by allowing for recirculation of fuel particles into and through the high-temperature combustion zones. This means that fuels ranging from anthracites to wood can be burnt in appropriately designed CFBC boilers at high combustion efficiencies of up to >99%.

The boiler efficiency is defined as the amount of heat energy absorbed by the working fluid (water/steam) divided by the total amount of heat energy of the fuel entering the boiler. The boiler efficiency for CFBC boilers, based on the high heating value (HHV) of the fuel, ranges from 75% to 92%. Several factors influence the boiler efficiencies. When fuels such as lignite and wood are fired, the high moisture content of the fuels will have a significant negative impact on the boiler efficiency. Other factors like steam parameters and boiler capacity also influence the boiler efficiency. Increasing the capacity of a boiler (by scaling-up) increases the boiler efficiency (Koornneef and others, 2007).

Thermal efficiency (also referred to as plant efficiency) is defined as the amount of electricity generated minus endogenous electricity requirement divided by the energy input. While affected by several factors, thermal efficiency can be improved by raising steam pressure and temperature as well as by adding a steam reheat cycle. The steam cycle for CFBC is comparable to that of pulverised coal installations. Whilst they all use a Rankine steam cycle, the main difference lies in the steam parameters. All the CFBC units currently in operation, except the Łagisza plant, employ subcritical steam conditions. They differ widely in their evaporation rate, steam pressure and steam temperature, which is site-/user-specific. With a subcritical cycle, the plant efficiency is of the same order as that of a pulverised coal plant, normally between 38% and 40% on a LHV basis (Henderson, 2003; Wu, 2006) or between 35% and 38% on a HHV basis (World Bank, 2008) depending on the steam conditions used. The first supercritical (SC) CFBC unit was commissioned in 2009 at Łagisza plant (Poland). The SC CFBC unit has a capacity of 460 MWe and burns hard coal. The operation in the first year was successful and the plant achieved a net efficiency of 43.3% (LHV basis) (Jäntti and Parkkonen, 2010; Hotta and others, 2010).

Availability and reliability

With the advances in CFBC technology and improved boiler design, the availability and reliability of CFBC boilers have increased over last two decades. Today, CFBC boilers can achieve an average availability of 90% or higher.

Operational flexibility

CFBC boilers can operate at baseload and in a load-following mode. The load-following capability is limited compared to PC boilers. Minimum load for a CFBC boiler is approximately 40%, without supplemental fuel and the technology is not well suited for on-off cycling. The bed material is susceptible to hardening if the bed temperature falls below its recommended operating range.

Fuel flexibility

A major advantage of CFBC technology is its ability to consume low quality fuels not typically used in a PCC boiler. These fuels are characterised by a high ash or moisture content, low heating value, and low volatile content and thus have lower costs. CFB boilers are capable of burning all types of coals, coal wastes and a wide variety of other fuels alternatively or simultaneously, and a wide variety of opportunity fuels can be used almost interchangeably without major, if any, plant modifications.

2.3.2 Environmental performance

Another main advantage of a CFBC boiler is the low emissions of NOx and SO_2. The combustion temperature of a CFBC boiler (800–900ºC) is significantly lower than a PC-fired boiler (1300–1700ºC), which results in a considerably reduced NOx formation. The majority of SO_2 formed during coal combustion is captured by limestone that is injected into the furnace. Typically, CFBC can achieve a sulphur removal efficiency of 90% at a Ca/S molar ratio of around 2 and increases to 95% for a Ca/S ratio of 3. The current state of the technology is such that in a CFB boiler more than 95% of sulphur can be removed with the use of in-bed sorbent injection.

The NOx emissions from a CFBC unit are only around one fifth of those produced by uncontrolled PCC. For most CFBC plants, NOx emissions are less than 400 mg/m^3, and modern new plants have lower emissions of less than 200 mg/m^3 (Henderson, 2003; Wu, 2006). Contrary to NOx, low combustion temperatures enhance the formation of N_2O. Reduction of N_2O can be achieved by increasing the volatile content of the fuel, air staging, NH_3 injection and sorbent addition (Koornneef and others, 2007).

Due to the application of the same dust collection technologies on both PC and CFBC systems, particulate emissions from CFBC installations are comparable to those of PC boilers and at most CFBC plants, emissions of 20—50 mg/m^3 can be easily achieved. Examples of the emissions from several CFBC units that burn different types of coal are shown in Table 1.

Table 1 Emissions from coal-fired CFBC units (Zhu, 2012; Sémédard and others, 2006; Hotta and others, 2010)

Red Hills power plant, USA, 2 x 250 MWe, commissioned in 2002	
Coal type	lignite
Sulphur content, wt%	0.9–1.25
Measured emissions, mg/m^3, dry flue gas at 6% O_2	
SO_2	325
NOx	260
Turów power plant, Poland, units 1–3: 235 MWe, commissioned in 1998-2000	
Coal type	lignite
Sulphur content, wt%	0.4–0.8
Measured emissions,mg/m^3, dry flue gas at 6% O_2	
SO_2	227–340
NOx	300–340
particulate	3.5–17.5
Tonghae power plant , South Korea, 2 x 200 MWe, commissioned in 1997-98	
Coal type	anthracite
Sulphur content, wt%	0.6–1.2
Measured emissions, mg/m^3, dry flue gas at 6% O_2	
SO_2	515
NOx	512
Łagisza power plant, Poland, 1 x 460 MWe (SC boiler), commissioned in 2009	
Coal type	bituminous coal
Sulphur content, wt%	0.6–1.4
Measured emissions (mg/m^3, dry flue gas at 6% O_2)	
SO_2	<200
NOx	<200
Particulate	30*

* guaranteed figure

Recent CFBC units have used post-combustion controls to further reduce emissions of NOx and SO_2 to meet the increasingly stringent emissions requirements. The control systems typically applied are selective noncatalytic reduction systems (SNCR) to reduce NOx emissions and dry FGD systems such as Flash Dry Absorber to reduce SO_2 emissions.

2.3.3 Plant sizes

Over the last ten years, one of the significant advances in CFBC technology has been the increase in the size of CFBC boilers. A number of the CFBC units commissioned recently are in the range of 250 to 330 MWe in size/capacity. The largest CFB unit currently in operation is the 460 MWe bituminous coal fired CFBC boiler at Łagisza Power Plant, Poland, which uses Foster Wheeler's once-through SC boiler design. Korean Southern Power Company (KOSPO) has recently chosen Foster Wheeler to supply four 550 MWe SC CFB boilers to its Samcheok Power Plant. The CFBC units will cofire bituminous coal and biomass fuel and are scheduled to start operation in 2015 (Foster Wheeler, 2011). A 600 MWe CFBC boiler is currently being commissioned at the coal-fired Baima Power Plant, China. This demonstration plant is China's first domestically designed 600 MWe SC CBFC unit. CFB manufacturer Alstom and Foster Wheeler claim that they are now ready to supply coal-fired SC CFBC units with capacity up to 800 MWe (Zhu, 2012).

2.3.4 Steam conditions

Almost all the CFBC installations currently in operation use subcritical steam conditions. In the past decade or so, the main focus of developing more efficient CFBC system is on increasing the unit size and the use of advanced steam cycles. The world's first supercritical, and also the largest CFBC boiler is the aforementioned 460 MWe unit at Łagisza Power Plant. The main steam pressure is 27.5 MPa, and the main and reheat steam temperatures are 560ºC and 580ºC, respectively. After the successful operation of the first SC CFBC unit since it started commercial operation in 2009, several more SC CFBC units are being installed around the world. The Novocherkasskaya GRES Unit 9, owned by Russian power producer OGK-6, is a 330 MWe coal-fired SC CFBC power generating unit supplied by Foster Wheeler. The steam conditions are 24.7 MPa/565ºC/565ºC. The unit is scheduled to come online in 2014 (Jäntti and others, 2012). As mentioned earlier, a 600 MWe SC CFBC boiler is currently being commissioned in China and four 550 MWe SC CFBC units are being built in South Korea, respectively. The design of the 600 MWe Chinese CFBC boiler is based on Alstom's CFBC technology and steam parameters of 24.5 MPa/571ºC(±5ºC)/569ºC(±5ºC) are used for the design (Mao, 2008). Steam parameters of 25.7 MPa/603ºC/603ºC are used in the design of the four 550 MWe CFBC units at Samcheok Power Plant, South Korea. When these units enter commercial operation in 2015, they will be the world's most advanced CFBC units (Jäntti and others, 2012).

2.3.5 Design variants

There are a number of manufacturers supplying CFBC boilers. Alstom and Foster Wheeler (FW) are currently the two largest producers of CFBC technology and both are active in various regions worldwide. Other main suppliers include AE&E Lentjes GmbH (formerly known as Lurgi Lentjes), Babcock & Wilcox (B&W) and Metso (formerly Kvaerner, acquired by Metso in 2007). There are also other suppliers that are active in their own region such as Bharat Heavy Electricals Ltd, ThyssenKrupp Industries India in India, Rafako SA of Poland and some Chinese boiler manufacturers.

The CFBC systems from the main manufacturers all share a similar basic configuration of the components found in CFBC technology as discussed above in Section 2.2. However, there are substantial differences in the design. The design variants of the CFBC technology offered by different manufacturers were reviewed in a recent report by the IEA CCC (Zhu, 2012). The main design differences are in the external or internal heat exchanger adopted, grid design (the grid of nozzles for feeding primary air into the combustor) and solid collecting systems. Foster Wheeler's CFBC system uses Compact CFB design with integrated recycle heat exchanger INTREX™. One of the distinguishing features of the Compact CFB design is the cooled, square solid separator placed directly next to the furnace, providing a 'compact' configuration. Recently, FW adopted the Benson once through boiler technology in its design of SC CFBC boilers.

Alstom's CFBC technology is based on a solid separation system with inlet ducts that are designed to accelerate and separate the particles prior to the cyclone itself. For larger units where four or more cyclones are required the pant-leg configuration is used in boiler design. Alstom's SC CFBC system also adopts the Benson once through boiler technology. Chinese boiler manufacturers licensed

Alstom's CFBC technology so their design has the similar feature of cooled cyclones in pant-leg configuration and external heat exchangers. AE&E Lentjes' CFBC system is also based on a pant-leg design with FBHE. Both once though and drum boilers are used in its CFBC system design.

Babcock & Wilcox's version, Internal Recirculating CFB (IR-CFB), features a two-stage particle separation system. Fluidised solids collide with the in-combustor beams (U-beams) and fall back to the bottom of the combustor. Smaller particles, which remain in the gas flow, may collide with a second set of U-beams placed outside the combustor. The fine solids fraction passing the U-beams are collected in the secondary stage of the solids separation system by a mechanical dust collector (MDC) or ESP. Similarly, Metso's CYMIC (CYlindricalMulti-Inlet Cyclone) boiler design features an internal hot cyclone. For both IR-CFB and CYMIC boiler designs, the need for a FBHE is absent as the solids are internally circulated. These designs are not suitable for CFBC boilers larger than 250 MWe. It should be noted that B&W, along with some other companies, are not pursuing larger power generating CFBC boilers. The various design features mentioned above will be discussed in more detail in Chapter 3.

2.3.6 Applications

CFBC technology is widely applied in chemical plants, steel work, utility and other industrial processes. The rapid spread of CFBC technology started in North America where the largest cumulative capacity is installed mainly in the USA. Europe followed with the installations of co-generation and coal-fired CFBC plants. The growth in capacity levelled off in Western Europe in the early 1990s but deployment increased in Central and Eastern Europe, especially Poland and the Czech Republic during the same period. CFBC technology has been employed for power generation for more than 20 years. Today, approximately 600 coal-burning CFBC power generating units have been installed and are in operation worldwide, and nearly 180 units with a total capacity of over 26 GWe currently are under construction or planned to be built (Platts, 2012). The total installed coal-based CFBC power generating capacity is more than 46 GWe. More than half of the installed capacity (around 52%) is found in Asia, while America and Europe account for 26% and 22%, respectively (PowerClean, 2004). In Asia, power plants using CFBC technology are in operation in China, Japan, South Korea and several other countries. The vast majority of the CFBC power generating units are installed in China. By 2008, CFBC power generating units, ranging from 3 to 300 MWe in size, accounts for more than 10% of total Chinese coal-fired power generation capacity. Among these, around 150 units are in the 100–150 MWe size-range and 13 units are 300 MWe in size, with a further 50 CFBC boilers with a unit size of 300 MWe planned to be built (Yue and others, 2009).

3 Developments in CFBC technology

Since the commercialisation of CFB technology began back in the late 1970s, there have been continuous technology innovations and improvements implemented into the designs to enhance performance, increase efficiency, improve reliability and operational flexibility in a cost effective way.

3.1 Furnace design

The design of a CFB furnace involves a careful evaluation of fuel and sorbent characteristics followed by a selection of operating parameters: temperature, gas velocity, gas/solids residence times, and solids circulation rates. Current design of the furnace is key to successful and efficient operation of a CFBC boiler.

3.1.1 Furnace dimensions

The geometry of the furnace has impacts on the mixing of fuel, air and sorbent, the bed temperature distribution, the heat transfer and so on. The upward flow of solids decreases with increasing furnace height. The heavier particles recirculate within the furnace resulting in decreased local density as a function of furnace height. Because the wall heat transfer rates are proportional to the solid density, furnace heights are limited in order to maximise the cost effectiveness of heat transfer surfaces. Balancing the consideration of the combustion efficiency and sufficient heating surface, the recommended furnace heights for CFBC units of varying sizes are given in Table 2. Similarly, there is also a limitation to furnace depth. With fuel and secondary air being injected through the side walls of the boiler, the furnace depth is limited, in general, to approximately 12 metres to ensure the penetration of secondary air and good mixing across the unit under all operational conditions. Table 3 shows the dimensions of several CFBC furnaces currently in operation.

Table 2 Recommended CFBC furnace heights (Lu and Feng, nd)

Fuel	Recommended furnace height, m						
	Size, kg/h						
	35	75	130	220	410	680	1000
Anthracite	20	21	26	32	36	43	54
Bituminous	20	20	25	29	34	39	50
Lignite	20	19	24	28	30	37	47

Table 3 CFB furnace dimensions (Venäläinen and Psik, 2004)

Furnace dimensions, m	Plant (size, MWe)			
	Łagisza (460)	JEA (300)	Turów 4–6 (262)	Turów 1–3 (235)
Width	27.6	26.0	22.0	21.2
Depth	10.6	6.7	10.1	9.9
Height	48.0	35.1	42.0	43.5

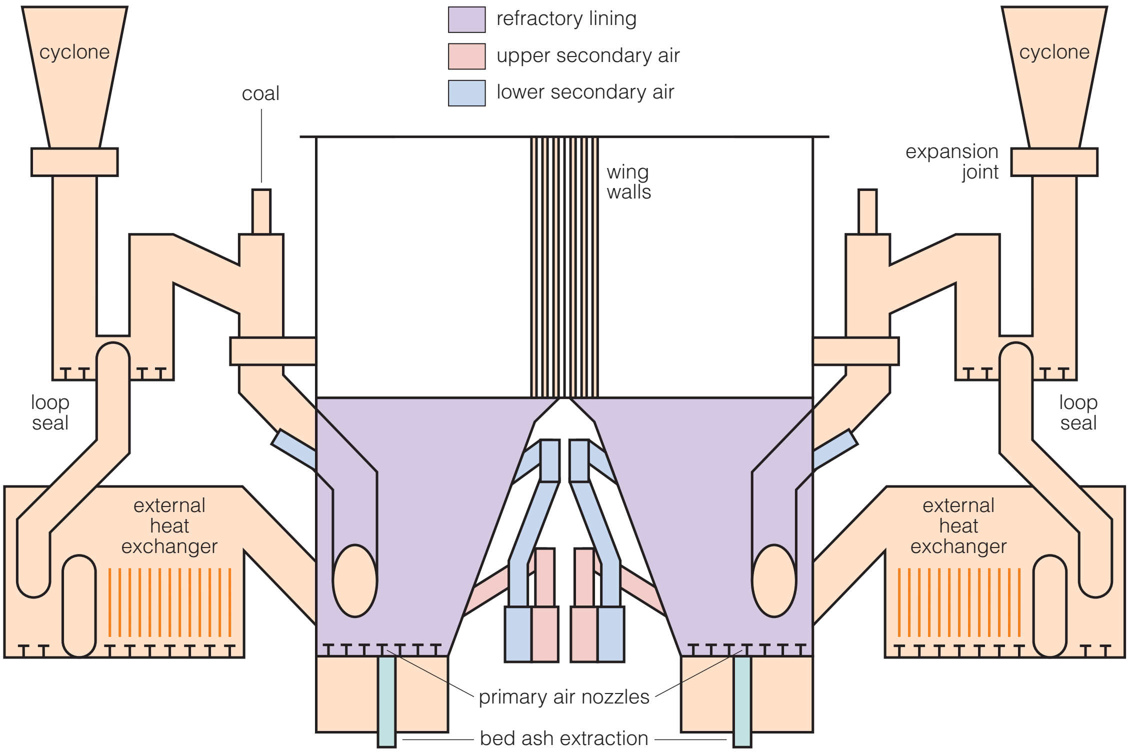


Figure 2 An overview of the pant-leg CFBC boiler design (Stamatelopoulos and others, 2005)

With maximum allowable furnace heights and furnace depths established, the main remaining variable in the scale-up process is the width of the furnace. By increasing the width of the furnace, the boiler cross-sectional flow area can be increased to accommodate increased firing rates while keeping flue gas velocities at normal levels. To overcome the limitation to furnace dimensions when scaling-up, Alstom has adopted the pant-leg design for large CFBC furnaces. In a pant-leg design, the lower furnace hopper is split (pant-leg hopper). Each hopper is equipped with separate fuel and air feeding systems. The secondary air is injected via the secondary air nozzles in the surrounding wall, as well as through nozzles located in the inner walls. By the separate control of primary air and secondary air to each hopper, an even fluidisation, uniform stoichiometries and bed material distribution are achieved. Figure 2 gives an overview of the pant-leg design.

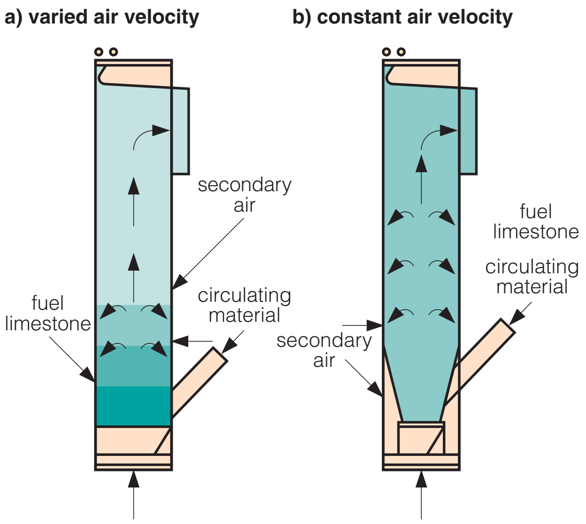


Figure 3 An overview of two types of lower furnace design (Lu and Feng, nd)

Compared with the pant-leg design, FW's CFBC furnace has one single fluidising grid under which there are several separate air plenums introducing primary air to furnace. The primary air flow through the air plenums is individually measured and controlled to ensure equal air flow to all sections of the grid and uniform fluidisation (Venäläinen and Psik, 2004).

3.1.2 Lower furnace designs

There are two types of design of the bottom of the furnace: varied air velocity and constant air velocity design, as shown in Figure 3. The former features same furnace cross section with varied air velocity. In the former design the furnace cross section is constant and the air velocity varies with the amount of air injected into it. The latter design features a tapered lower furnace structure. This design is most commonly used in modern CFBC boilers (Lu and Feng, nd).

In the tapered lower furnace design the grid area is approximately 50% of the upper furnace cross section. This provides high internal turbulence of the fluidised bed and enables efficient mixing of fuel, absorbent and secondary air. As the unit size increases, the depth of the unit remains constant to ensure good mixing of bed material and air in the lower furnace. The width of the unit increases and cyclones are added as required to maintain gas velocities at optimum levels. Operating results from large CFBC plants with tapered lower furnace design have shown that the furnace is reasonably insensitive to operational disturbances such as unbalanced fuel feeding.

The tapered lower furnace design has been adopted by major CFBC boiler manufacturers such as FW and Alstom (*see* Figure 2). The tapered portion of the furnace is covered with refractory. At the joint of the taper and vertical water wall tubes, FW uses a 'kick-out' tube design as shown in Figure 4 to prevent tube erosion above the refractory (Chen and Jiang, 2011).

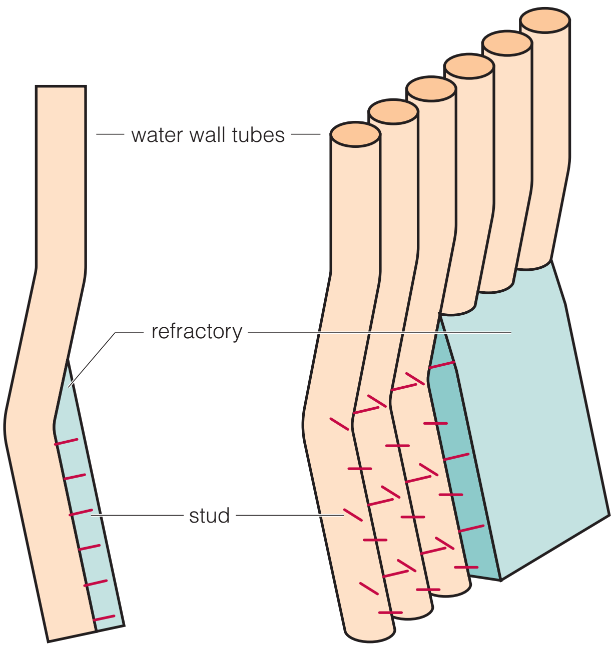


Figure 4 FW's 'kick-out' design (Chen and Jiang, 2011)

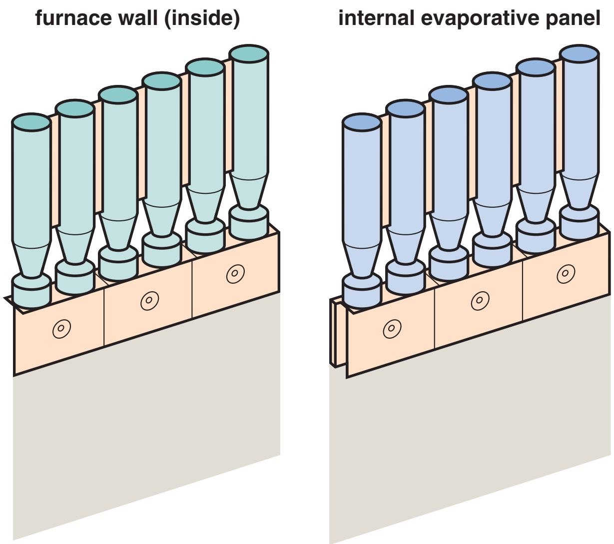


Figure 5 B&W's RDZ design (Maryamchik and Wietzke, 2005)

In B&W's CFBC furnaces, the membrane tubes at the upper edge of the refractory in the lower furnace are protected from erosion by its patented Reduced Diameter Zone (RDZ) design. The RDZ design (Figure 5) features a reduced diameter tube section with a specially shaped ceramic tile placed at the top edge of the refractory to minimise tube erosion at the interface. The reduced diameter tube section on each tube slopes away from the solids falling down the wall along the surface profile of the tube panel, thereby eliminating the discontinuity adjacent to the tube. The CFBC furnace with RDZ installed at Ebensburg CFBC plant (USA) resulted in increasing intervals between the outages from six months (dictated by refractory interface maintenance requirements) to a year or more (Maryamchik and Wietzke, 2005).

3.2 Solid separation systems

One of the key component in a CFBC boiler is the solid separation system. A solid separator separates the entrained particles from the flue gas leaving the furnace and returns the hot solids to the lower furnace to maintain the desired uniform temperature in the combustion chamber. The efficiency of the solid separation system impacts the capture rate of the fines fraction of the solids entering the separators, which in turn affects absorbent (limestone) utilisation and fuel carbon burn-out. Maintaining a high separation efficiency in the solids separators is key to achieving high combustion efficiency, reduced limestone consumption, and high sulphur capture efficiency. In the development of CFBC technology, two main types of separators have been applied in commercial CFBC installations: cyclones and impact separators.

3.2.1 Cyclones

By far the most commonly used solid separation system is the cyclone. In the early years CFBC boilers used a hot cyclone design which consisted of a steel shell lined with thick (about 300 mm) multi-layer refractory. The hot cyclone design has a relatively low capital cost. However, it has high maintenance costs because the refractory structures experience cracking and sometimes sustains major damage causing unplanned shut-downs. The outages caused by refractory damage account for nearly 20% of all the plant annual unavailability. In addition, hot cyclones require longer cold start-up times and thus consume more start-up fuel. With the development of water- or steam-cooled cyclones, the cyclone interior walls are lined with a thin layer (25–50 mm) of refractory held in place by a dense pattern of metal studs, while the exterior walls are covered with insulation and lagging to prevent heat losses. The modern cooled-cyclone design has reduced the annual unavailability in small CFBC boilers caused by refractory damage to 2%, and the decrease is more significant in larger CFBC boilers. The improved cooling design also minimises refractory maintenance and reduces the maintenance and operating costs with longer service life and higher availability (Halikka, 2007; Chen and Jiang, 2011).

In the early 1990s, Foster Wheeler (FW) introduced a Compact Separator that uses pentagonal shaped membrane water walls with a thin layer of refractory inside the separator to smooth out the corners, as shown in Figure 6. By using a membrane water wall, the need for an expansion joint between the cyclone and the furnace, as used in other type of cyclone design, is eliminated. This greatly reduces the potential of hot expansion joint failures and therefore increases availability of the boiler. Compared to the round-cyclone-type design, the compact cyclone is formed from flat rather than curved tubing panels which reduces the footprint of the boiler (Chen and Jiang, 2011).

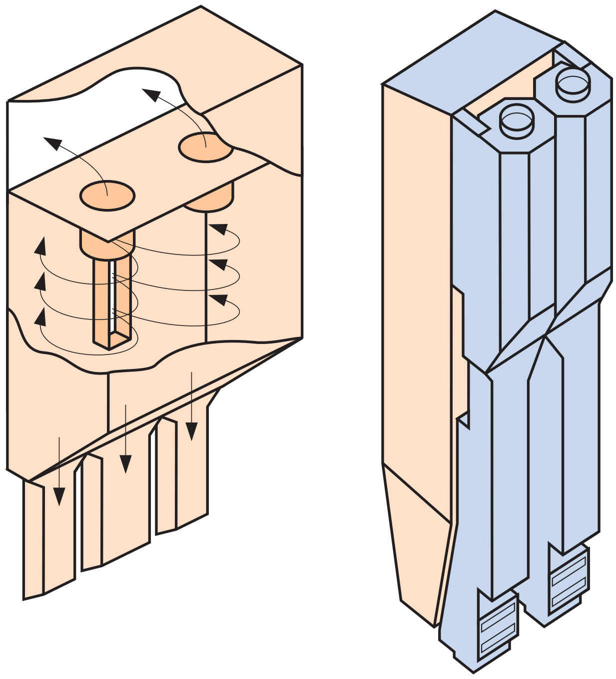


Figure 6 Foster Wheeler's Compact Separator (Chen and Jiang, 2011)

Since 1993, Tsinghua University in Beijing, China, has been working on the development of water-cooled square cyclones. Compared with traditional round cyclones of with same capacity, a square cyclone is smaller in size, has a shorter start-up time, is simpler and less-costly to engineer and construct but has lower separation efficiency. Tsinghua University adopted a curved inlet in the design of the water-cooled square cyclone to accelerate particles and hence improve the separation efficiency. Figure 7 shows a water-cooled square cyclone with a curved inlet. Based on the operating experience of 75 t/h and later 130 t/h CFBC boilers with water-cooled square cyclones, a 220 t/h commercial demonstration CFBC unit with advanced water-cooled square cyclones was commissioned in 2001 at Weihai Heat and Power Cogeneration Plant in Shandong, China. The boiler design bears similar features to that of FW's Compact CFBC boiler. Two square cyclones made of planar membranes are located between the furnace and the backpass. The front wall of the square cyclone functions as the rear wall of the

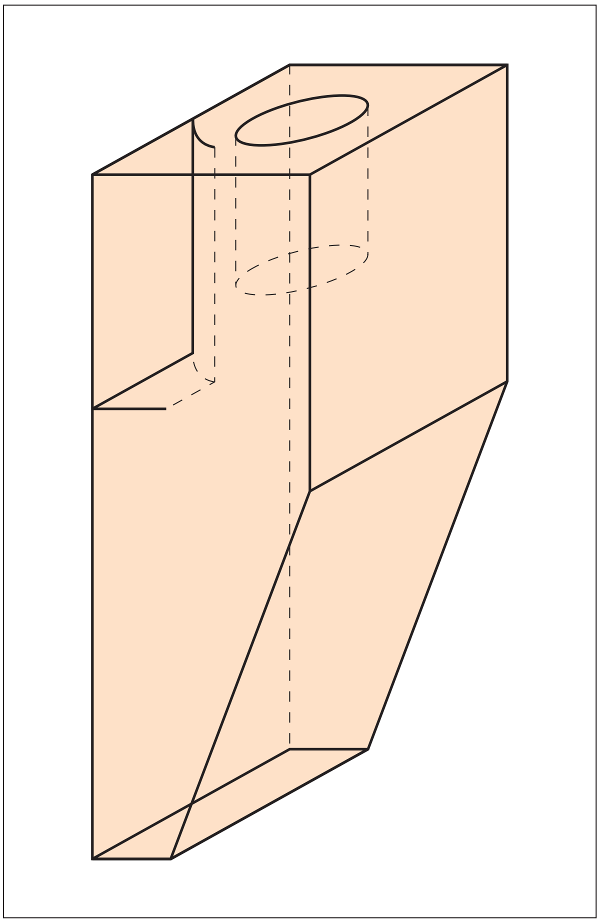


Figure 7 Schematic of Tsinghua University's water-cooled square cyclone with curved inlet (Lu and others, 2007)

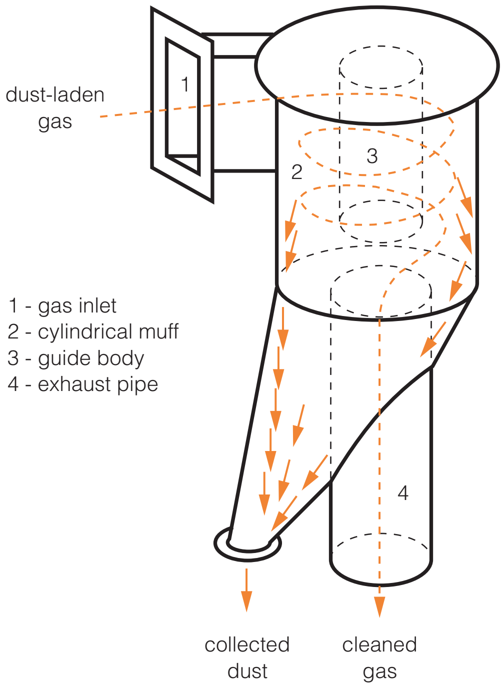


Figure 8 Down-exhaust cyclone separator (Chen and others, 2003)

furnace, and the rear wall of the square cyclones functions as the front wall of the backpass. With this arrangement, the boiler becomes more compact and has a smaller footprint. Also, the use of expansion joints is eliminated. Due to the water-cooling, low grade carbon steel can be used to make the studs that connect to the membrane water walls. Tests and operating results showed that the water-cooled square cyclone had low pressure drop, improved availability and separation efficiency comparable to that of traditional round cyclones (Lu and others, 1999, 2001, 2007; Wang and others, 2005).

To improve the efficiency and to reduce the physical size of the CFBC's solid separation systems, a number of optimised or novel designs have been developed over the years. Alstom's CFBC technology is based on a separation system with improved design to the inlet and outlet ducts. The inlet ducts are designed to accelerate and separate the particles prior to the cyclone itself. The design of the vortex finder length and location is also optimised.

Other solid separation systems with novel designs include louvre-type separators (staged CFBC boiler) and down-exhaust cyclone separators (Π-shaped CFBC boiler). In a Π-shaped CFBC boiler, the Chinese-patented down-exhaust cyclone is located after the superheaters in the horizontal convection pass and above the backpass so the boiler has a Π-shaped configuration. As shown in Figure 8, a down-exhaust cyclone consists of a cylindrical shell which is joined by an inclined cone, a guide body, and a downward exhaust pipe. The solid-laden gas enters the cyclone tangentially and moves down in a rotational movement along the guide body. The cleaned gas exits the cyclone through an exhaust pipe located at the bottom of the cyclone. Test results showed that this separator was capable of achieving a separation efficiency of around 99% while handling high solids loadings such as those in CFB boilers, at a pressure drop of around 0.4 MPa. Both louvre-type separator and down-exhaust cyclone have been applied on dozens of small CFBC boilers (Chen and others, 2003).

3.2.2 Impact separator

B&W's CFBC boilers feature a two-stage solids separation system consisting of an impact-type primary solids separator and a secondary multi-cyclone dust collector. The primary stage impact solids separator is located at the furnace exit collecting the bulk of the solids (95–97%) that are then returned to the furnace by gravity. As shown in Figure 9, the primary separator is arranged as an array of U-shaped vertical elements (U-beams). The secondary separation stage, typically a multi-cyclone dust collector (MDC), is located in the lower gas temperature region (250–510ºC) of the boiler convection pass.

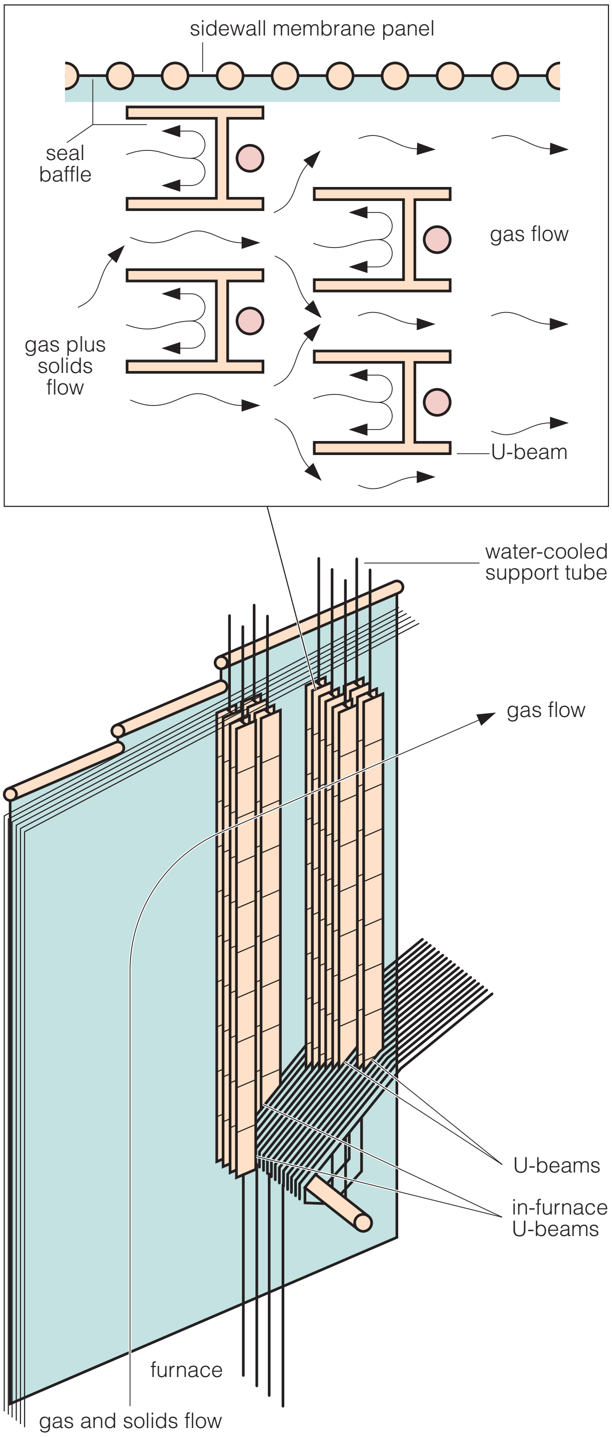


Figure 9 B&W's U-beam solid separator (Maryamchik and Wietzke, 2010)

The main advantages of the two-stage solids separation design include (Maryamchik and Wietzke, 2010; Belin and others, 2001):

- compact design requires 20–30% less building volume than cyclone-based CFB boilers – critical for repowering projects;
- low auxiliary power: the total pressure drop across the two-stage separator is 1 kPa, and also, high-pressure air blowers for fluidisation of returning solids are not needed;
- minimal refractory use: The amount of refractory used in IR-CFB boilers is 80–90% less than that used for similar capacity CFB boilers with non-cooled hot cyclones and 40–50% less than CFB boilers with cooled cyclones;
- low maintenance due to the low overall amount of refractory, reduced diameter zone design, low furnace exit velocity, and an absence of hot expansion joints;
- dynamic load change and wide turn-down ratio (5:1).

The design of the U-beam separator has been evolving over the last two decades. The earliest design had eleven rows of U-beams, all installed externally to the furnace with solids recycle through non-mechanical controllable L-valves. The second generation of U-beam separator had two rows of in-furnace U-beams discharging collected particles (about 70% of incoming solids) directly to the furnace and seven rows of external U-beams with solids recycle through L-valves. The next generation of the U-beam separator consisted of two rows of in-furnace U-beams and three or four rows of external U-beams with all solids internally recycled within the furnace. The latest design features a total of four rows, of which two are located in the furnace and two externally. While each U-beam in earlier designs was made as a single piece hung from the top, in the current design it consists of segments, each segment being supported independently from a water-cooled tube (*see* Figure 9). Supporting tubes for the first three rows (along the gas flow) are the furnace rear wall tubes; those for the last row are fed from a separate header. This design allows independent thermal expansion of each segment and eliminates the need for the hopper under external U-beams that was required for providing a room for thermal expansion of long stainless steel beams hung from the roof. As a result, simpler construction/engineering and cost reduction of the U-beam separator have been achieved.

During the same period, the design of the MDC has also been improved and the current design has a top gas inlet and a side gas outlet. The the MDC solids recycle system has evolved from a dense-phase pneumatic transport (first generation) to a dilute-phase pneumatic transport to gravity conveying. The latest MDC improvement involves the cyclone elements material. The cyclone sleeves and spin vanes were made of high hardness cast iron for reliable operation but this was associated with certain maintenance expenses. Replacing cast iron material with ceramics has resulted in a marked reduction of wear and maintenance as well as associated costs (Maryamchik and Wietzke, 2005, 2010).

3.2.3 Optimised arrangement of solid separators

Since the separation efficiency of cyclones tends to decrease as their physical sizes/diameters are increased, large CFBC boilers use the cyclone sizes proven in smaller size units. Although a large CFBC boiler will require the size and/or number of cyclones to increase, they will be of a proven size and design. Also, an optimised arrangement of the cyclones and their respective inlet ducts will ensure that gas and solid loading of the cyclones are within a proven range. Figure 10 shows the scale-up strategy used by Alstom. The same scale-up principle is also adopted by FW. The design module of a nominal 100 MWe furnace with two cyclones is used as a building block in designs of large CFBC boilers. For CFBC boilers larger than 300 MWe, cyclones are arranged in parallel on opposite (front and rear) furnace walls (Stamatelopoulos and others, 2005; Fan and others, 2006).

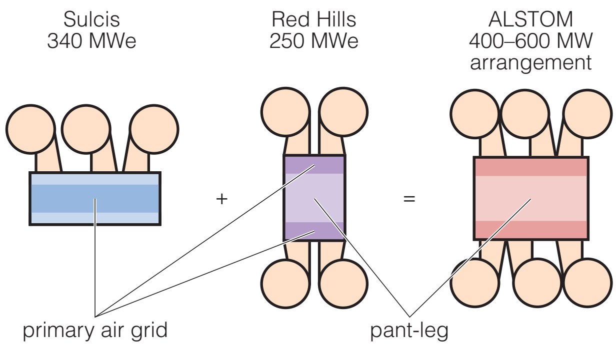


Figure 10 Alstom's scale-up principle for a 600 MWe CFBC boiler with six cyclones (Stamatelopoulos and others, 2005)

3.3 External heat exchangers

Heat transfer surfaces are used for heat duties such as evaporation, superheating and reheating in CFBC power plants. Furnace walls are used as heating surfaces, and heat exchangers are placed in the convective pass and in-furnace panels. Evaporative duty is performed by the furnace walls, which consist of bundles of pipes that are arranged horizontally or vertically. For a CFBC boiler of small capacity, the furnace wall surfaces are sufficient for the evaporative duty. As boiler capacity increases, the ratio of furnace wall surface area to enclosed volume decreases. Typically, additional evaporative surfaces are provided by using wing walls that protrude into the furnace and are connected in parallel with the furnace walls in a single pass water flow arrangement. For CFBC boilers larger than 300 MWe and with reheat, it may not be possible to perform all the required heat duty in the furnace and backpass. As a result, external heat exchangers (EHE) are needed to provide additional heat duty for larger boilers.

Bubbling fluidised beds are normally used for EHE to extract heat from the hot circulating bed material that is collected by the solid separators. Fluidised bed heat exchangers (FBHE) have relatively high heat transfer rates. The major advantages of using an EHE are its ability to adjust the superheat and reheat steam temperature, and to control the combustion temperature. Solids from the furnace are collected by the separators and are directed, using a water cooled ash control valve, from below the cyclone hopper at temperatures of 845–900ºC to a FBHE for the purpose of performing additional boiler heat duty. A series of heat exchanger bundles, which can perform superheater, reheater, and/or evaporator duties, can be located in the bed. The solids are fluidised with the air and cooled down to temperatures around 600ºC and then returned to the lower furnace (Stamatelopoulos and others, 2005, Lu and Feng, nd).

Due to a low fluidising air velocity (typically <0.3 m/s) and fine particle sizes (~200 µm), the potential for erosion of the heating surface is minimised. As the heat exchanger is fluidised with air and not exposed to corrosive elements in the flue gas stream, the problem of corrosion is also eliminated. In addition, with the use of an ash flow control valve, one can control the heat transfer to the immersed tube bundles, which in turn controls the furnace temperature and the steam temperature without spray injection. By standardising tube bundle arrangements and by utilising a modular approach, scaling-up the unit size can be accommodated without developing new FBHE designs. With increasing boiler size, the number of FBHEs is increased and may equal the number of cyclones. The high cyclone efficiency ensures sufficient solids flow to the FBHE for all unit sizes and boiler loads (Wu, 2006; Stamatelopoulos and others, 2004; Morin, 2003).

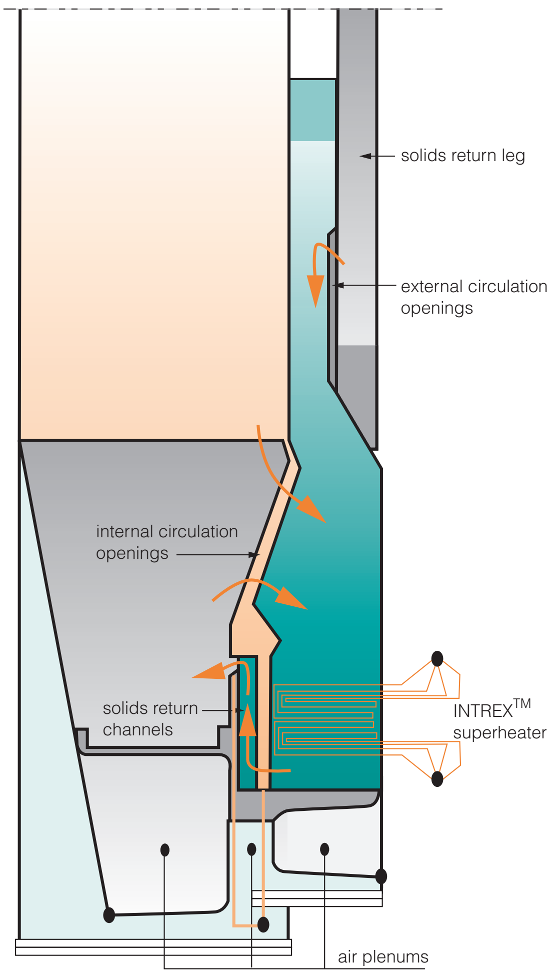


Figure 11 FW's INTREX™ heat exchanger (Wu, 2006)

The CFBC boilers by Alstom and AE&E Lentjes GmbH usually feature pant-leg design with EHEs. B&W's IR-CFB and Metso's CYMIC system do not have EHEs because the solids are internally circulated by a cyclone that is integrated in the furnace.

FW developed an improved FBHE design called an integrated recycle heat exchanger (INTREX™), which integrates the heat exchanger waterwall with the furnace water-steam system and the return channel. In addition to cooling the externally circulated solids, openings in the furnace rear wall provide access for additional solids to circulate internally through the heat exchanger tube bundles ensuring sufficient hot solids to the INTREX™ heat exchanger at all loads. Figure 11 shows the layout of the INTREX™ heat exchanger. The solids from the separator flow through the solid return leg and enter the bubbling bed heat exchanger. The cooled solids are returned to the lower furnace via the solids return channel (external circulation). With internal solid circulation, additional hot bed materials are taken from the furnace to the INTREX™ through openings in the furnace rear/common wall. Any excess solids spill back to the furnace via the openings. The solids flow rate through the tube bundles is controlled by controlling the velocity of fluidising air to the lift legs that return the solids to the lower furnace. By controlling the solids flow rate through the chamber of the INTREX™ superheater, the heat absorption can be varied giving operational flexibility to control furnace and/or superheat steam temperature. The heat transfer coefficient from solids to the tubes can also be adjusted by changing fluidisation of the solids in the INTREX™ chamber. The INTREX™ has the following potential advantages over alternative systems (Walkowiak and Wójcik, 2001; Venäläinen and Psik, 2004; Goidich and Hyppänen, 2001):

- integrated system eliminates the need for expansion joints and the associated maintenance;
- internal solid circulation allows superheater heat absorption even at low loads when the external solids circulation is low;
- hot solid flow and hence heat transfer are controlled by changing the fluidising air velocity rather than a control valve, thus minimising maintenance need.

There are currently around 20 CFBC units in operation which have INTREX™ heat exchangers including the first SC CFBC unit at Łagisza power plant.

3.4 Scale-up

Over the last ten years, one of the significant advances in CFBC technology has been the increase in the capacity of CFBC boilers. This was motivated by the desire to take advantage of economy of scale from the standpoint of capital cost and plant efficiency. Several market leaders have been actively developing larger-scale CFBC boilers. Alstom, based on the operating experience gained from their 300 MWe CFBC plants, is continuing to work on scaling-up towards 600 MWe and is developing a SC CFB boiler. Alstom's 600 MWe SC CFBC boiler features a pant-leg design with three cyclones and up to three FBHEs on each pant-leg side, and supercritical once-through boiler technology (Morin, 2003; Stamatelopoulos and others, 2005). Similarly, FW have been working on developing advanced designs for larger scale units with more compact systems and infrastructure, including the incorporation of advanced steam conditions, with fuel flexibility as an integral part of the overall concept. FW has developed a modular design approach allowing it to offer commercial 600 and 800 MWe SC units. In China, work has been carried out jointly by Tsinghua University and several Chinese boiler manufacturers to develop 600 MWe SC CFBC boilers. The 600 MWe SC CFBC demonstration unit at Baima Power Plant is currently under commissioning. Figure 12 shows some of the recent coal-fired CFBC installations and CFBC projects that are planned or under construction. The steady increase in the unit size of CFB boilers over the years is clear to see from Figure 12. Most

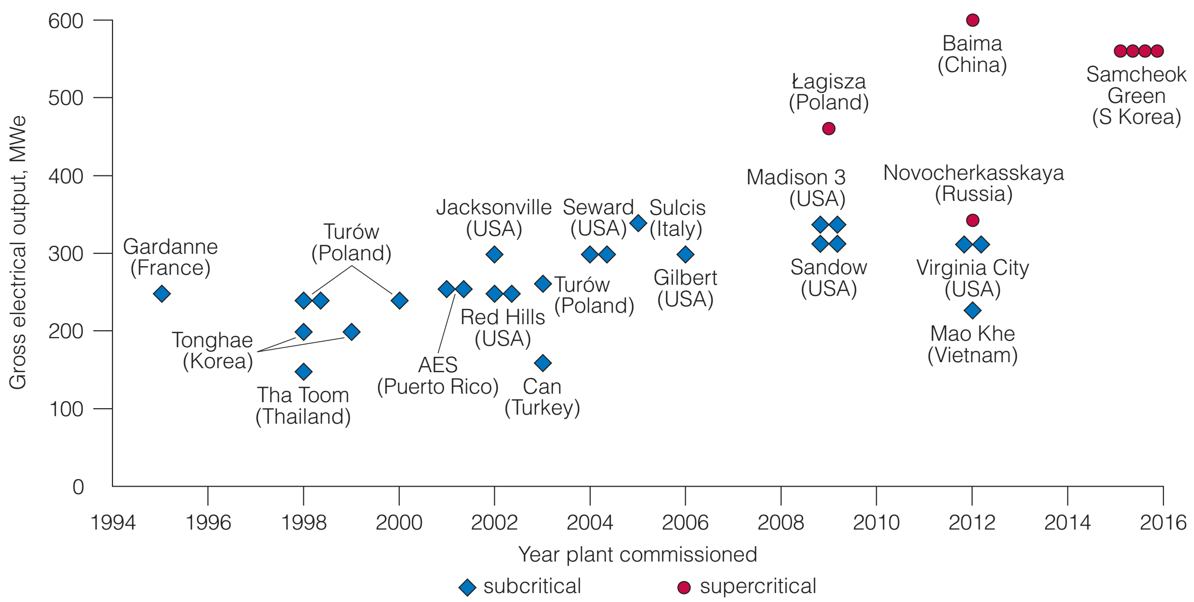


Figure 12 Recent CFB units installed, planned or under construction (Zhu, 2012)

of the CFBC units commissioned recently are in the range of 250 MWe and 330 MWe. The largest CFBC unit in operation is the 460 MWe hard coal fired CFBC boiler at Łagisza power plant, Poland, which uses FW's once-through SC boiler design. Korean Southern Power Company (KOSPO) has recently chosen FW to supply four 550 MWe SC CFBC boilers to its Samcheok Power Plant. The CFBC units will fire bituminous coal and biomass fuel and are scheduled to start operation in 2015 (Foster Wheeler, 2011; Jäntti and others, 2012; Zhu, 2012). Further scale-up of CFBC units to above 800 MWe is possible.

3.5 Advanced steam cycle with once-through boiler technology

The main focus of the development of more efficient CFBC system is on increasing the capacity and the use of advanced steam cycles. There has been a continuous improvement in efficiency due to economies of larger scale and increases in the steam parameters as a result of the introduction of new creep resistant materials. Operation above the critical steam conditions significantly increases the plant efficiency and results in reduced fuel consumption, and lower emissions of SO_2, NOx and CO_2 per megawatt of power output. Currently, CFBC boilers, with a few exceptions, have primarily been configured as drum type subcritical units which utilise natural or assisted circulation as the means for cooling the furnace enclosure tubes. The drum boilers are typically limited to main steam pressure below 19.3 MPa because their natural circulation principle is based on the density difference between steam and water that diminishes at higher pressures. To move CFBC technology to advanced steam cycle conditions, Alstom and FW have both adopted once-through boiler technology in their designs of SC CFBC boilers.

A key to the design of once-through boilers is to cool sufficiently the furnace enclosure tubes to avoid overheating under all operating conditions and to minimise the tube temperature differences between the adjacent tubes. This has typically been accomplished, in PCC boilers, by designing the furnace tubes for high fluid mass-flow rates. To provide high mass-flow rates, the evaporative furnace walls have been designed in a multiple pass arrangement or a single pass with spiral tubing arrangement. However, CFBC technology imposes stringent requirements on water wall tubing. The high ash loading in the furnace means that the spiral-wound tubing is not feasible for CFBC furnaces because the inclined tubes would be subject to erosion. A new development started in the 1980s led to the design of vertical evaporator tubing with low mass flux and with the use of rifled tubes. The tube arrangements used in the once-through boiler design are shown in Figure 13. The vertical tube arrangement with rifled tubes has the following advantages:

- allowing a relatively low mass-flow rate (about 1000 kg/m^3s) at full load, with a 'natural circulation' flow characteristics similar to that of drum boilers;
- reduced evaporator pressure drop and therefore lower power consumption;
- low minimum load and simple start-up;
- reduced slagging and erosion on furnace wall due to parallel gas flow;
- cost-effective fabrication and assembly because the vertical, self-supporting furnace enclosure tubes use a standard top support system that does not require attachment of separate support straps.

When applying the SC once-through boiler technology to a CFBC process there are also other merits. The nature of CFB combustion means a CFBC furnace operates at a comparatively low combustion temperature, and the vertical and radial temperature distribution throughout the furnace is relatively uniform. The low and uniform heat flux throughout the entire CFBC furnace is a result of relatively low combustion temperatures, lack of burners and no distinct flame with high temperature and high radiation, and the circulating solids that have a relatively constant temperature within the furnace. In PCC, the burner flames cause a high temperature zone, resulting in high heat fluxes locally and higher temperatures in the boiler tubes. As a result of the low and uniform operating temperature, the heat flux to the enclosure walls of the furnace is considerably lower than in a PCC furnace and therefore, the furnace tubes can be designed for low mass-flow rates without concern for tube overheating

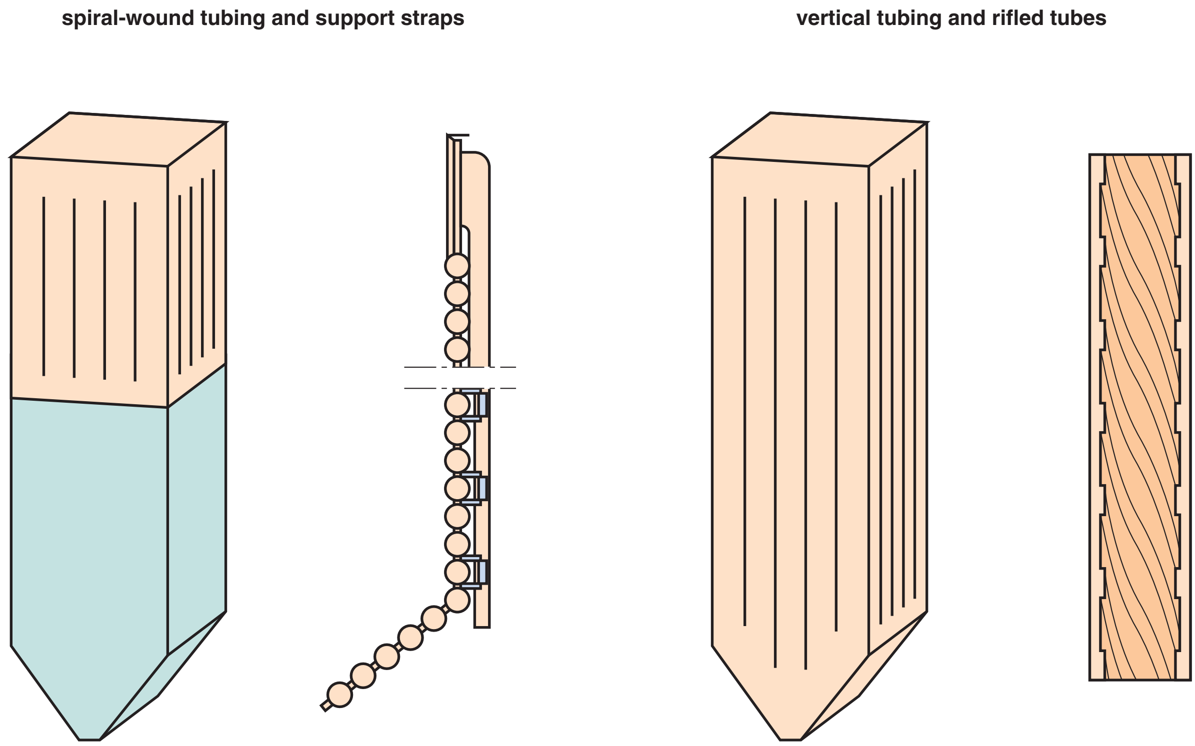


Figure 13 Wall water tube arrangements used in once-through boiler designs (Lundqvist and other, 2003)

(Lundqvist and others, 2003; Walkowiak and Wójcik, 2001; Goidich, 2000). In addition, the relatively low and uniform temperature within a CFBC furnace can minimise differential temperatures that may cause fatigue cracking, and reduce slagging due the lack of hot spots leading to reduced maintenance requirements.

Based on its experience from design and operation of once-through supercritical pulverised coal fired boilers and extensive studies, Alstom developed a once-through supercritical CFBC boiler design that features a parallel arrangement of all furnace waterwall tubes with small diameters to keep the mass flow rates within acceptable limits. A circulation pump is added to provide sufficient cooling flow through the evaporator tubes during start-up and shut-down or low load operation (Stamatelopoulos and others, 2005; Morin, 2003).

FW has licensed Siemens' Benson vertical low mass flux once-through technology for use in its SC CFBC boiler designs. This technology is centred on an evaporator design and steam generators using the Benson design which have features such as a highly efficient water/steam cycle as a result of supercritical pressures and high steam temperatures, insensitivity of steam output and steam temperature to fluctuating fuel properties, and the capability for rapid load changes due to variable-pressure operation and short start-up times (Lundqvist and others, 2003). The main advantages of this technology include (Goidich, 2001):

- low pressure loss: a single up-flow evaporative pass with low mass flow rates results in low steam/water pressure losses, and therefore low auxiliary power consumption;
- simple support system: with vertical tubing, the furnace enclosure tubes are self supporting and do not require special support straps to account for thermal growth;
- minimum tube temperature imbalance: with low mass flow rates, the most heated tubes gets the highest flow rate because of a natural circulation flow characteristic;
- full variable steam pressure: since a single up-flow evaporative pass is used, full variable pressure over the operating load range can be used to better match steam and turbine blade temperature for cycling operation.

The world's first SC CFB unit at Łagisza power plant, Poland, started commercial operation in 2009. The coal-fired CFB boiler was supplied by FW using the Benson vertical low mass flux once-through technology integrated with the Compact CFB boiler design, and steam parameters of 27.5 MPa/560ºC/580ºC. Another 330 MWe coal-fired once-through SC CFB unit in Novocherkassk, Russia is scheduled to start operation in 2014. The steam conditions of 24.7 MPa/565ºC/565ºC are applied in the design of the Novocherkassk CFBC plant. FW also sold four 550 MWe coal-fired once-through SC CFBC boilers with steam parameters of 25.7 MPa/603ºC/603ºC, to Korean Southern Power Co Ltd, which are scheduled to come online in 2015 (Jäntti and others, 2012).

Recently, investigations into the technical feasability and economics of CFBC boilers with USC (ultra-supercritical) steam parameters have been conducted. The study of a conceptual design of USC CFB boilers by FW found that despite the CFB's relatively low combustion temperature, the 700ºC steam temperature of advanced USC cycles can be accommodated by operating FW's INTREX™ FBHE with internal solids circulation. The physical arrangements of the 400 MWe and 800 MWe USC units reflect conventional FW CFB boiler configurations and can be deployed without the need for research and development (R&D) work. The use of advanced USC conditions (nominally 35 MPa/704ºC/704ºC) will increase the net efficiency of the 800 MWe CFB plant to 43.3% on a HHV basis (Robertson and others, 2009; Fan and others, 2006). As with the development of USC PCC technology, a key to the successful development of future USC CFBC technology is the availability of high temperature metal materials.

3.6 Availability and reliability

Availability is commonly used as an indicator for the performance of power plants. It is calculated by dividing the number of hours a plant is able to generate output by the total number of hours for a given period of time. The availability can be used to measure the reliability of a design or the effectiveness of operation and maintenance (O&M). The availability is reduced due to forced outage (problems) and planned outage, together called down time. Problems that caused down time were associated mainly with the boiler section, solid separation, fuel feed and preparation section. Problems in the boiler are caused by erosion and corrosion of the furnace walls, agglomeration of ash and bed particles and tube failure in the steam production section. Early problems with erosion and corrosion were dealt with by adding refractory to exposed parts. Development in the material used for refractory and boiler design reduced the thickness of the material and overall failure rates.

One of the major problems that caused forced outages in the early years was the hot cyclone failure. The heavy refractory-covered hot cyclone often experienced cracking and sometimes sustained major damage causing unplanned shut-downs. The outages caused by refractory damage accounted for almost 20% of all the plant annual unavailability. The heavy refractories also required significant maintenance during scheduled maintenance outages. The development of water- or steam-cooled cyclones has significantly improved the availability and maintainability of CFBC plants (Halikka, 2007). Figure 14 compares the unavailabilities of utility-scaled CFBC boilers with a hot cyclone and a modern cooled cyclone.

Over the past 20 years, several improvements in refractory system designs, fuel and sorbent feed system designs, and ash extraction equipment design have been made that adequately address the initial problems encountered with these system components. As a result, the availability of CFBC systems have been improved and are considered to be generally equivalent to PCC boilers. Koornneef and others (2007) studied the availability data of CFBC plants between 1985 and 2004 from various sources and found that in the period 1985-90 the availability ranged from 50% to 70% and since then the availability has not fallen below 80% and averaged around 90%. The improvement in the availability of B&W's CFBC plants over the years is demonstrated in Table 4. Today, CFBC plants can achieve an average availability of 90% or higher (Black&Veatch, 2007; Koornneef and others, 2007).

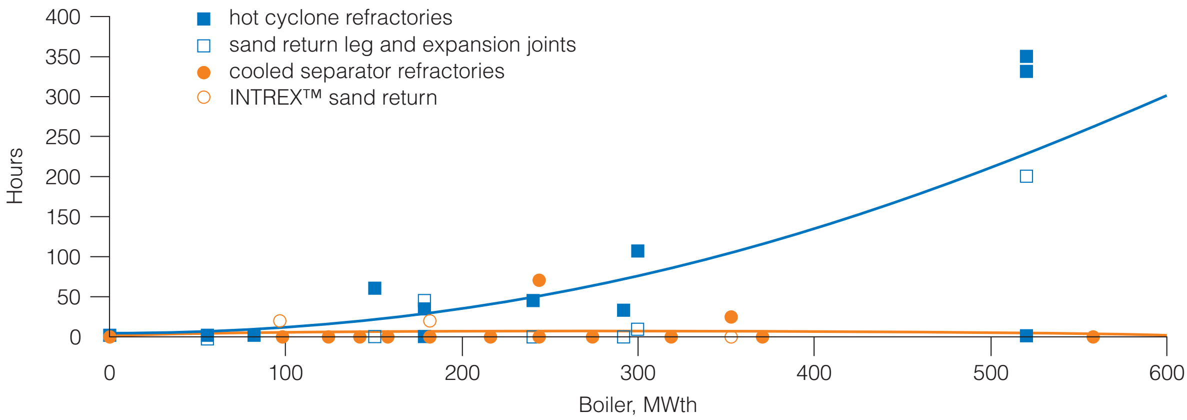


Figure 14 Average annual down time (hours) of CFBC boilers with a hot cyclone and a modern cooled cyclone (Halikka, 2007)

Table 4 Improvement in the availability of B&W's CFBC plants (Maryamchik and Wietzke, 2010)

	Ebensburg CFB, USA		CFB at Southern Illinois University, USA		Indian Kanoria 1 (commiss-ioned in 1996)	Indian Kanoria 2 (commiss-ioned in 2005)	Indian Rayon (commiss-ioned in 2006)	Indian Saurashtra Cement (commiss-ioned in 2008)
Reported year	1991-2003	2004-2009	1997-2003	2004-2009	1997-2010	2006-2010	2007-2010	2009-2010
Plant availability*	90.5	94.7	92.6	95.7	90.55	93.91	96.26	93.11

* all data in % of total time available

3.7 Fluidised bed ash coolers

CFBC boilers produce a large amount of bottom ash at high temperatures (about 800–900ºC) which needs to be cooled to about 175–200ºC before it can be handled by ash handling conveyors and other handling equipment. A well-designed system should incorporate an ash cooler to extract and recover the excess heat of the ash prior to ash disposal. Various forms of bottom ash cooling devices have been developed. The two types of bottom ash cooler that are commonly used in CFBC power plants are the water-cooled screw cooler and the fluidised bed ash cooler. With a fluidised bed ash cooler, the bed material is extracted from the furnace bottom to a stripper zone. Here, the ash is fluidised by air at a suitable velocity in order to strip the required amount of fines (typically unburnt carbon and unutilised limestone) from the stream and return them to the furnace. This increases carbon combustion and limestone utilisation efficiencies. The balance of the material, which is primarily coarse, passes through a cooling zone, where it is cooled to an acceptable temperature before discharge to the ash drain system. The cooler and the stripper recover the heat from bottom ash, thereby raising the boiler efficiency (Wu, 2006).

A number of problems such as blockage of solids transfer conduits between the furnace and the cooler, accumulation of coarse particles that tend to settle along the ash path preventing fluidisation and rendering the cooler inoperable, and high maintenance of expansion joints between the cooler and the furnace are known to have been experienced in operating bottom ash fluidised bed coolers. These problems are being addressed by innovative and improved designs. The B&W's recent CFBC design, as shown in Figure 15c, features an integral fluidised bed cooler that shares a common wall with the

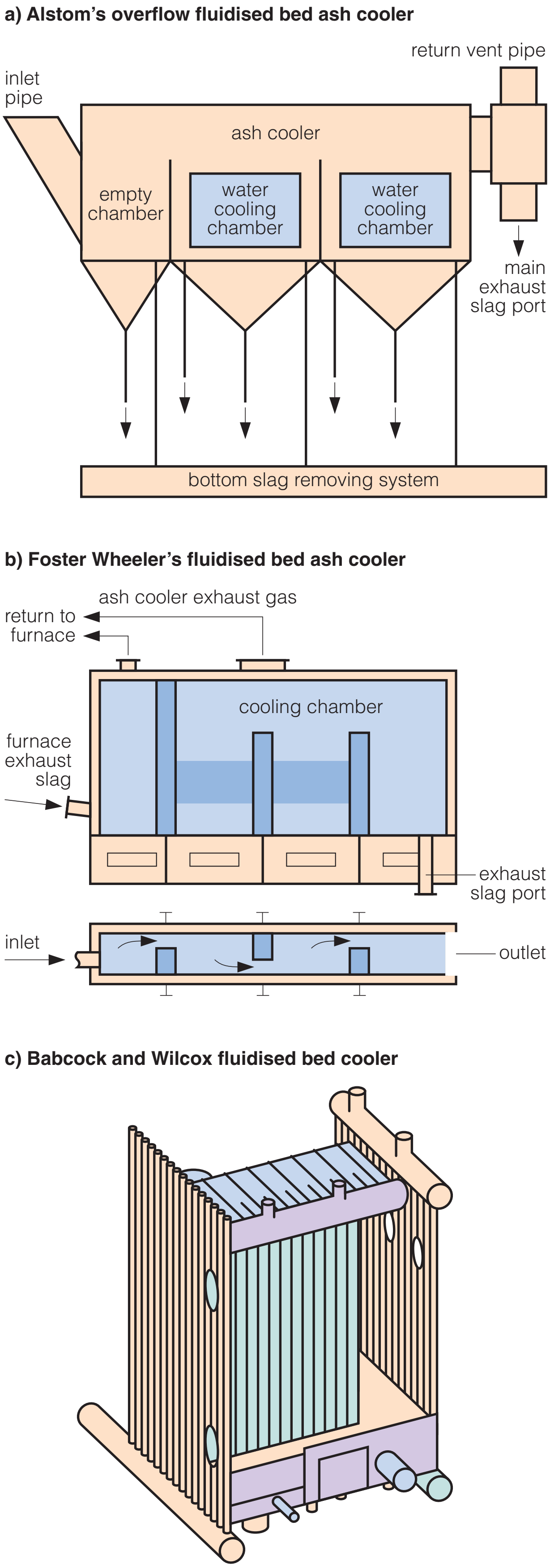


Figure 15 Various designs for fluidised bed ash cooler (Zeng and others, 2009; Maryamchik and Wietzke, 2008)

furnace. The remainder of the cooler enclosure is made of water-cooled tubes included in a down-flow path of the furnace water circulation circuit. This minimises the difference in thermal expansion, thus eliminating the need for expansion joints between the furnace and the cooler. Instead of the conduits, simple openings in the common wall provide for the transfer of solids from the furnace to the cooler and of the cooling/fluidising medium from the cooler to the furnace. The cooler is divided into a series of sections to enhance the heat transfer. An opening for discharging ash from the cooler is located on the floor of the last section along the ash path. The Ash discharge rate is controlled to maintain a preset furnace pressure profile. The fluidised bed level in the cooler is self-adjusted as a function of the pressure differential between inlet and outlet openings of the cooler, independently of the discharge rate. To prevent coarse particles from accumulating in the cooler, they are removed from the entrance section located immediately after the inlet opening. The elevation of the bubble caps in this section is lower than that in the furnace and the following sections of the cooler. This facilitates accumulation of coarse particles in this section and prevents their transport to the downstream sections of the cooler. As the accumulation of coarse particles is detected, their discharge is initiated through the opening in the floor of the entrance section. Their cooling to an acceptable temperature is achieved by spraying water into the bed at the discharge opening (Maryamchik and Wietzke, 2008).

Alstom developed the overflow fluidised bed ash cooler (*see* Figure 15a) in which the bottom ash flows in a 'fluidised overflow' mode. Its advantages include high heat transfer rate, high stability of bed pressure in the cooler, and reduced average particle size and fluidising air flow rate resulting from the removal of coarse particles. However, it may suffer problems such as obstruction to ash removal leading to the last chamber being almost empty, coking in the empty chamber, and overheating when coal with high ash content is burnt (Zeng and others, 2009). Figure 15 shows examples of designs for a fluidised bed ash cooler.

Work to improve the design of ash coolers is continuing. In China, a mixed-flow fluidised bed ash cooler is being developed based on the existing fluidised bed ash cooler designs. The mixed-flow fluidised bed ash cooler consists of two chambers. Ash particles enter the ash cooler in a 'mixed-flow' mode containing 'underflow' and 'fluidised overflow'. Coarse and fine particles are separated in the selective chamber where the coarse particles are cooled by fluidising air and then discharged from the bottom of the selective chamber. The fine particles are fluidised and flow into a water-cooled chamber in a 'fluidised overflow' mode. The fine particles have sizes smaller than 4 mm and the water-cooled chamber operates under bubbling fluidised bed conditions under which the potential for erosion and abrasion to the heating surface is minimised. Also, the flow rate of the fluidising air can be maintained at a low level under such conditions. Tests have been carried out on a CFBC power plant and the results are encouraging (Zeng and others, 2009).

3.8 Co-combustion

A major advantage of a CFBC system is its ability to consume all types of coal, coal wastes and a wide variety of other fuels either individually or cofired. Also, a wide variety of opportunity fuels can be used almost interchangeably without major, if any, plant modifications. As global warming and climate change have become pressing issues, there are urgent needs for global action at all levels to reduce CO_2 emissions. Utilisation of biomass as a sustainable energy source is already seen as one of the key options in the short and medium term for mitigating CO_2 emissions. It was estimated that with CFBC technology a 35% of CO_2 emission reduction could be achieved by substituting 15% of coal with biomass fuel (Jäntti and others, 2007). Figure 16 shows the reduction in CO_2 emissions with increase in plant efficiency and in the proportion of biomass in fuel. There has been increasing interest in cofiring biomass or waste derived fuels (WDF) with coal for power generation. CFBC technology has developed to meet the requirements for cofiring in large power generating boilers as well as in smaller combined heat and power generating boilers.

CFBC technology is well suited for cofiring coal with biomass and/or WDF. However, fuel characteristics and combustion behaviours vary drastically from one fuel type to the next and these differences must be considered in both the design and operation of the boiler. When biomass as a fuel is compared with coal, the most important differences can be found in the variability of physical and chemical properties, higher moisture contents and low nitrogen and sulphur contents of biomass fuels. The moisture content of biomass has a particularly large influence on the combustion process and on the resulting efficiencies. Low ash fuels such as woody biomass may need sand added to the bed material. Agricultural biomass can have higher concentrations of potassium and sodium. When combined with the higher alkali metal concentration, and higher chlorine concentrations inherent to agricultural material, the potential for corrosion will increase. In CFBC systems, the cyclone separates the coarse particles from the flue gas and only the finer fly ash passes to the flue gas duct. Dependent upon the properties, this fly ash may form ash deposits on tube surfaces of the superheater or economiser in the flue gas duct. Also, condensing alkali vapours may contribute to the fouling of the cooled heat-exchanger surfaces. These deposits may reduce the heat transfer to the steam tubes and disturb or even clog up the flow of the flue gas through the heat-exchanger. They may also cause corrosion of the heat-exchanger tube metal. However, such problems can be limited with proper boiler design, suitable boiler operation, alternative bed materials or additives, and most effectively by co-combustion with coal as coal ash will dilute or even adsorb the harmful components of biomass/WDF ash, thereby reducing or stopping slagging and fouling. Design varies with the fuels used in the installation depending on a number of fuel quality factors. The main factors are: heating value, ash content, corrosion potential of combustion by-products and the preparation the fuel requires (Tillman and others, 2009; Hiltunen and others, 2008; Koornneef and others, 2007). Figure 17 shows the challenges of CFBC design associated with various types of fuel.

Fouling and corrosion caused by biomass and other difficult fuels have been a topic of extensive research in the past two decades and continues at the present (Hiltunen and others, 2008; Zabetta and

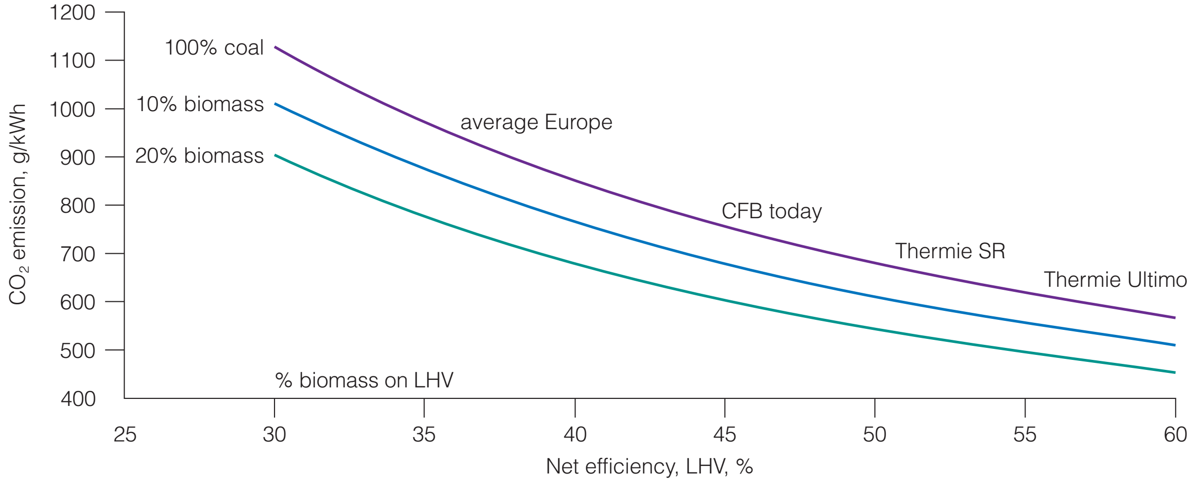


Figure 16 Reduction in CO_2 emissions with increase in plant net efficiency and in the proportion of biomass in fuel (Jäntti and others, 2007)

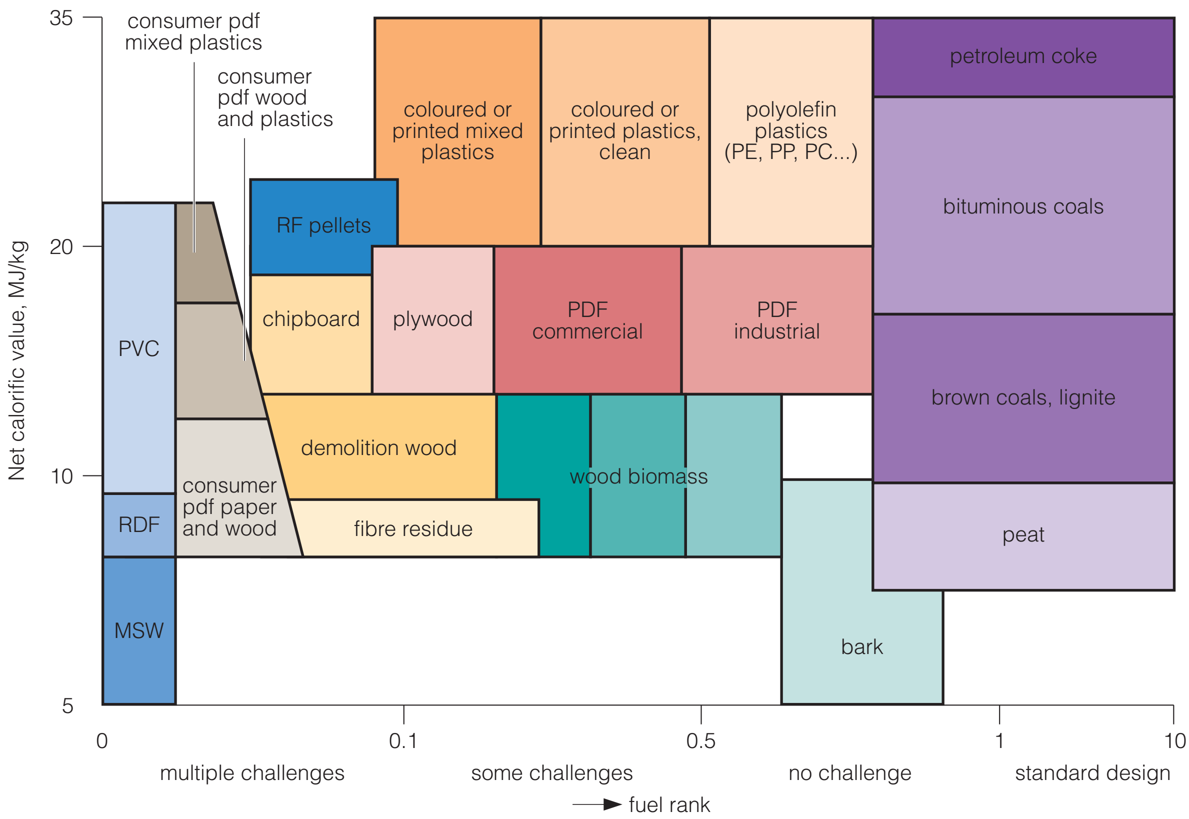


Figure 17 A categorisation of fuels regarding to the challenges on CFBC boiler design (Koornneef and others, 2007)

others, 2008; Hupa, 2012). The study results and the lessons learned from firing such fuels led to modifications in design and operating parameters such as fuel preparation and feeding, coarse material removal from the fluidised bed, and preventing agglomeration of bed material or ash.

The main operational challenges threatening boiler availability have been related to the fuel feeding and bottom ash discharge systems. Modifications in fuel preparation and feeding are necessary in a CFBC unit that cofires coal with biomass and/or WDF to ensure efficient combustion and to maintain the desired operating conditions. Depending on the type/property of the fuel, different preparation processes that suit each or a group of similar fuels is required. The sizes, locations and the ways various fuels are fed into the furnace may vary and these need to be carefully considered. Apron-type dosing feeders have been developed to facilitate controlled fuel flow even with demanding WDF. Large openings in fuel feeding bottom ash system together with directional primary air nozzles are designed for effective coarse material handling. When WDF is burnt, coarse materials such as wires, metal pieces and stones may be found in the bed material. These large particles need to be removed to prevent defluidisation of the bed. The design features of the coal and WDF cofired CFBC boiler installed at Neumünster (Germany), supplied by AE&E AG, are described in detail by Anderl and others (2005). The open nozzle grid for bottom ash discharge is utilised to ensure the removal of coarse particles. FW's CFBC boilers that fire biomass or waste feature a bottom grid named StepGrid, which has flat nozzles arranged in rows. All rows converge towards the bottom ash chutes, thus promoting the removal of large inert bodies (Lehtonen and Strömdahl, 2012; Tillman and others, 2009).

A common measure to tackle bed agglomeration is to increase the bottom ash removal along with increased makeup material flow. In this way the amount of alkali that coats the bed material is controlled, and growing agglomerates are removed. If advantageous, the amount of makeup can be reduced by re-circulating a screened portion of bottom ash, from which troublesome fractions have been removed by mechanical sieving.

Superheater corrosion is mostly associated with chlorine compounds (principally alkali chloride salts) condensed on superheater tube surfaces. Fouling and corrosion problems in the convective superheaters can be prevented by careful choice of steam temperature for each superheating stage and by using effective heat surface cleaning methods. Commonly, lower steam parameters are used in CFBC plants burning biomass/WDF. However, this measure causes the process to deviate from its optimum operating conditions, thus losing efficiency and economy. FW's solution to high-temperature corrosion is to use INTREX™ as the last stage superheating/reheating, and refractory-lined separators as second superheating. Chlorine content is much lower here than in the flue gas heat recovery area, and corrosion rates are significantly limited. This arrangement also allows a lower steam temperature to be used in convective superheating/reheating sections where the risk of high-temperature corrosion is highest (Góral, 2012; Barišic and others, 2008; Zabetta and others, 2008). The sootblowing strategy for minimising fouling and corrosion of the heating surfaces includes water gun sootblowers in the empty pass and typically steam sootblowers at the convective superheaters (Lehtonen and Strömdahl, 2012).

In brief, since the commercialisation of CFB technology in the late 1970s, there have been continuous technology innovations and improvements in the designs and process engineering to enhance performance, increase efficiency, improve reliability and operational flexibility in a cost effective way. Over the last ten years, the most significant advances in CFBC technology have been the increase in the size of CFBC boilers and the adoption of advanced steam conditions. Today, depending on the fuel quality, SC CFBC boilers with capacities up to 800 MWe are commercially available. Other main technical innovations and developments incorporated into the latest CFB plants include modern solid separation systems, the use and optimised design of EHEs, and improved designs of furnace and fluidised bed ash cooler. In addition, recent research and studies on fouling and corrosion caused by biomass and other difficult fuels led to modifications and optimisations in design and operating parameters of CFBC boilers that cofire coal and biomass and/or waste derived fuels. A large number of multifuel-fired CFBC plants have been installed and been operated successfully. Coal and peat are common fuels in multifuel CFB installations together with wood or wood-based fuel.

More recently, the potential application of carbon capture to CFBC systems has been investigated intensively. The oxy-fuel CFB firing process is currently being developed and will be discussed in the following chapter.

4 Oxy-fuel CFBC technology

The power industry has continuously innovated and improved coal combustion technologies and engineering designs to be more competitive environmentally and economically. Today, power generators are facing the challenge of reducing CO_2 emissions, which is likely to lead to substantial changes in the way the power is produced and consumed. For CO_2 emissions control, intensive R&D is ongoing to develop and commercialise technologies for carbon capture and storage (CCS). For PCC and CFBC boilers, oxy-fuel combustion systems are under development.

The basic concept of oxy-fuel firing with today's PCC and CFBC technologies is to replace combustion air with pure oxygen. However, firing coal in pure oxygen would result in a flame temperature too high for existing furnace materials. In order to allow conventional combustion equipment to be used, the combustion temperatures have to be moderated by recycling a proportion of the flue gas and mixing this with the incoming oxygen. In oxy-fuel PC and CFB combustion coal is burnt in a mixture of recirculated flue gas and oxygen. The remainder of the flue gas that is not recirculated comprises mostly CO_2 and water vapour. The water vapour is easily separated by condensation, producing a stream of mainly CO_2 ready for treatment and purification prior to transport and storage.

Oxy-fuel combustion is one of the main options for CO_2 capture from combustion plants. Oxy-fuel combustion process is applicable to virtually all fossil-fuelled boiler types and is a candidate for retrofits and new power plants. An optimised oxy-fuel combustion power plant will have ultra-low emissions. The current state-of-the-art is such that a greenfield oxy-fuel combustion plant could be built or an existing plant retrofitted using existing technologies. However, such plants would not be optimised due to a lack of data or proven computer models of oxy-fuel combustors, boiler systems or CO_2 recovery systems. In order to obtain better understanding of the fundamentals of oxy-fuel firing systems, of the character and distribution of ash and slag of coal during oxy-fuel combustion, and to support development of improved systems and CFD models/modelling tools, oxy-fuel combustion facilities at various scales are being constructed or are in operation and extensive research and investigations are being carried out around the world.

4.1 Oxy-CFB combustion system

Figure 18 shows a simplified process flow of an oxy-CFB combustion plant. It consists of an air separation unit (ASU), an oxy-CFB power generating plant, and a CO_2 treatment unit. Oxygen is mixed with recirculated flue gas, which creates a mixture of primarily O_2 and CO_2 (as well as H_2O) used as oxidant and is fed to the boiler, together with solid fuel and sorbent for sulphur capture. The combustion products leaving the furnace (mainly CO_2, H_2O vapour, and solids) flow through a cyclone where most of the solids are separated from the flue gas. For combustion temperature control, the solids collected in the cyclone are split between an uncooled stream that flows directly back to the furnace and a stream flowing through an external heat exchanger, where the solids are cooled before returning to the furnace. The heat of the flue gas leaving the cyclones is recovered by an economiser (ECO) and gas heat exchanger located in the backpass before ash removal at the ESP. The flue gas is further cooled down to condense most of moisture at the quenching tower. The recirculated flue gas can be optionally extracted before the quenching tower as a hot/wet gas recycle, or after as a cold/dry gas recycle. The balanced flue gas is then sent to the CO_2 purification and compression unit (CPU).

In an oxy-CFB boiler, the control of combustion temperature can also be achieved by recirculating cooled solids to the furnace through a FBHE meaning that minimal flue gas recirculation is required. This allows higher oxygen concentration to be used in oxy-CFB combustion providing potential for

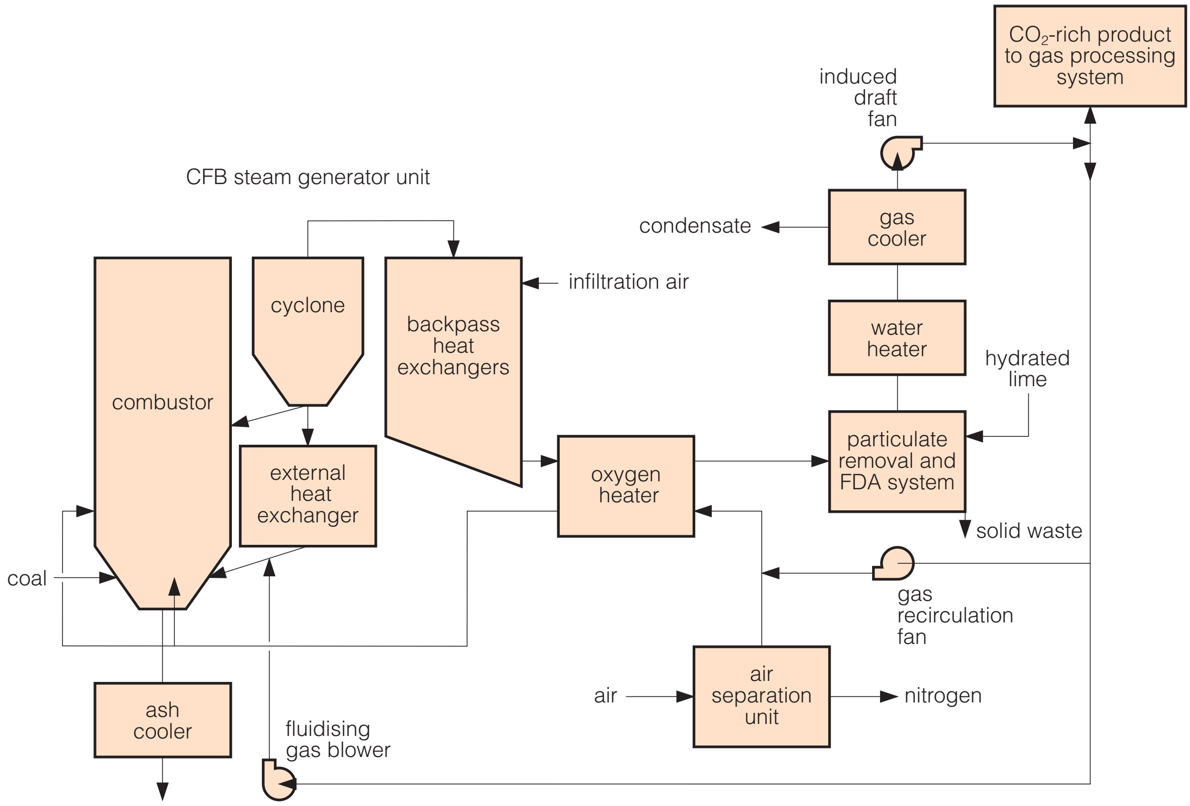


Figure 18 A simplified flow diagram of an oxy-CFB combustion process (Nsakala and others, 2005)

cost savings and efficiency improvements but also requiring entirely new boiler designs. Reduction of flue gas recycling also means decrease in boiler size and some of the auxiliaries consumption leading to potentially more compact and less expensive oxy-CFB boiler than the equivalent air-fired CFBC boiler in a new unit application. For dual oxy- and air-fired operation or for retrofit applications, the CFBC boiler would retain similar size as the air-fired design.

Oxy-CFB boilers have all the advantages of CFBC technology such as fuel flexibility and low emissions. Additional advantages of oxy-CFB include the reduced unit size with associated reductions in capital and operating costs, reduced air ingress due to large parts of furnace operating at slightly over atmospheric pressure, and simple implementation since CFBC units do not need sophisticated burner designs and management.

4.2 Oxy-CFB boiler design challenges

The design of oxy-CFB boiler is believed to be of similar nature to air-fired CFBC boilers. In principle, normal CFBC boiler designs with reasonable modifications can be applied if the ratio is chosen so that the adiabatic combustion temperature is close to that of air firing, while selecting a much higher oxygen concentration. The primary impacts of oxy-fuel combustion on the boiler concept and design is associated with the reduced combustion gas flow due to the removal of nitrogen present with air firing and the differences in the thermal and radiative properties of the gas comprised of mostly CO_2.

4.2.1 Differences between air and oxy-fuel combustion conditions

Studies in laboratory- and pilot-scale experiments showed that oxy-fuel combustion differs from air combustion in several ways, for example, reduced flame temperature and delayed flame ignition.

Many of these effects can be explained by differences in gas properties between CO_2 and N_2, the main diluting gases in oxy-fuel and air combustion respectively. CO_2 has different properties from N_2 such as density, heat capacity, diffusive and radiative properties, which influence both heat transfer and combustion reaction kinetics. Due to the higher molecular weight of CO_2 (which is 44) compared to N_2 (28), the density of the flue gas is higher in oxy-fuel combustion. The heat capacity of CO_2 is also higher than N_2. The diffusion rate of O_2 is slower in CO_2 than in N_2 (0.8 times that in N_2). Under oxy-combustion condition, the furnace gases contain higher levels of CO_2 and H_2O, both having high emitting power.

Due to the differences in gas properties, to attain a similar adiabatic flame temperature (AFT) an oxygen level of about 30–35% is required in the gas entering the boiler. The high concentrations of CO_2 and H_2O in the oxy-fuel furnace gases, however, result in higher gas emissivity, so that the radiative heat transfer characteristics similar to that of an air-fired system will be attained when the O_2 level of the gases entering the furnace is less than that required for the same AFT (Wall and others, 2009).

4.2.2 Boiler size

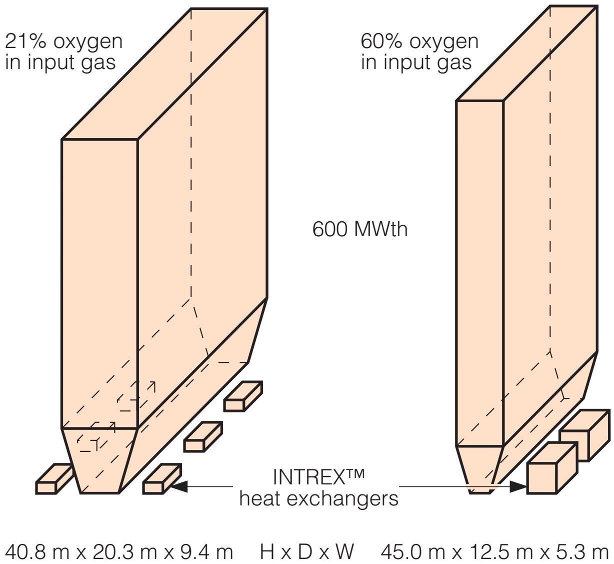


Figure 19 Size comparison of an oxy-CFB furnace and an air-fired CFBC furnace (Jäntti and others, 2007)

The effect of oxy-fuel combustion on the size of an oxy-CFB boiler depends on the oxygen concentration selected. The higher the O_2 concentration is, the smaller the furnace will be. Table 5 compares the flue gases produced by a CFBC boiler under air- and oxy-firing conditions. It is apparent from Table 5 that in oxy-fuel combustion, the flue gas mass/volume flow decreases considerably with increasing O_2 content. The reduced flue gas flow results in significant size and cost reduction in the combustor, cyclone, convection pass, oxygen heater, ducts, fans, and other equipment. Figure 19 compares the size of an oxy-CFB with an air-fired CFB boiler. As shown Figure 19, when a mixture of 60% O_2 and 40% recycled flue gas is used as an input gas to an oxy-CFB boiler with a capacity of 600 MWth, the furnace volume is 63% smaller than an air-fired CFBC furnace of the same capacity (Jäntti and others, 2007).

Table 5 Comparison of composition and mass/volume flow of flue gases from air-fired CFBC and oxy-CFB (Nsakala and others, 2005)

	Air	30% O_2	70% O_2
Flue gas composition, % volume			
N_2	74.78	0.81	0.74
CO_2	14.49	82.78	74.91
H_2O	7.40	13.05	20.97
O_2	3.31	3.31	3.31
Relative flow, % volume (mass)			
In furnace	100 (100)	89 (66)	36 (28)
Net produced	100 (100)	23 (16)	23 (16)

4.2.3 Heat duty and heat transfer

The main effect of increasing O_2 content is the steep rise of the adiabatic combustion temperature, which will increase the need of heat transfer in the CFBC furnace and its share of the overall boiler heat duty. With higher O_2 concentrations, however, the volume of fluidising gases is reduced. As a result, furnace cross section and volume is decreased while the heat transferred in the furnace needs to be increased. For example, the heat duty from the combustion process into steam cycle are similar for the two boilers shown in Figure 19. However, due to the smaller size the share of total heat duty of the oxy-CFB furnace is increased from 68% to 85%, while the furnace wall area is decreased by 36% (Jäntti and others, 2007). This creates a challenge to manage the furnace temperature levels and to locate and develop designs for heat exchangers in the hot loop of oxy-CFB boiler.

The total heat absorption is the same in both air and oxy-fuel combustion excluding the parallel feedwater heater (PFWH) heat absorption of the latter. The main differences occur in the convection pass, furnace and external heat exchanger. Figure 20 shows the boiler heat adsorption distribution of a CFBC system in air- and oxy-firing mode. The convection pass heat absorption for oxy-firing is about 41% of that of air-fired due to the reduced flue gas flow. Similarly, the furnace heat absorption for oxy-firing is about 39% of the air-fired value due to its significant reduction in boiler size whilst the external heat exchanger heat absorption for oxy-firing is about 68% of the total heat duty as compared to about 20% for air firing (Jukkola and others, 2005).

As discussed in Section 4.2.1, due to the differences in gas properties the higher CO_2 and H_2O concentrations with oxy-firing result in increased non-luminous radiative heat transfer from the gas. The calculated impact of the increased radiation is that the heat transfer coefficient in the convective pass will be about 10% higher with oxy-firing. In CFBC system, however, hot solids are the dominant heat transfer medium in the furnace and external heat exchanger (EHE) and therefore changes in the gas radiative properties are expected to have little effect. These were confirmed by the results from Alstom's bench- and pilot-scale (3 MWth) tests which found the in-furnace heat transfer coefficients for oxy-firing were comparable to air-firing whilst the heat transfer coefficients in convection pass were higher with oxy-firing than with air-firing (Nsakala and others, 2005; Levasseur and others, 2009).

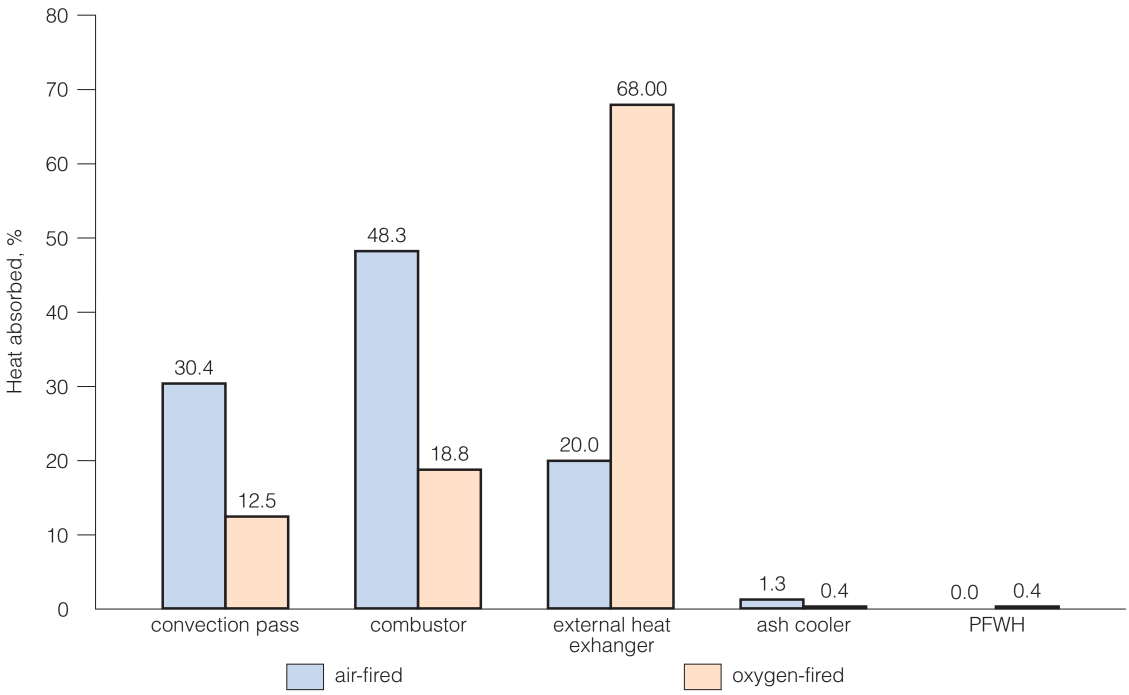


Figure 20 Boiler heat adsorption distribution of a CFBC system in air- and oxy-firing mode (Jukkola and others, 2005)

4.2.4 Pollutants emissions

SOx and NOx emissions from coal combustion in enriched O_2 have been investigated in several studies. The fuel characteristics and combustion temperature were found to affect in-furnace SO_2 capture and hence the SO_2 emission levels. Tests carried out at Alstom's and Foster Wheeler's bench- and pilot-scale oxy-CFB facilities showed that there was generally an optimum temperature for SO_2 capture in an oxy-CFB furnace. The optimum temperature is ≥900ºC (1650°F) for anthracite and petroleum coke, and is around 843°C (1550°F) to 870ºC (1598°Cfor bituminous coal whilst the optimum temperature is lower for lignite and other low rank fuels (Nsakala and others, 2005; Hotta and others, 2011; Hack and others, 2012a).

Czakiert and others studied the combustion of brown and bituminous coal in a laboratory-scale oxy-CFB test rig. The temperature of 700ºC, 860ºC and O_2 concentration of up to 60% were used for oxy-combustion of lignite, whilst 757ºC, 1009ºC and O_2 concentration of up to 35% were used in oxy-combustion tests of bituminous coal. No SO_2 absorbent was added into the bed material. Their results showed that SO_2 emissions from lignite combustion increased under oxygen-enriched conditions. The increase in temperature and O_2 concentration, however, had little effect on the conversion of fuel sulphur to SO_2 during combustion of bituminous coal. It was observed that higher O_2 content promoted desulphurisation during combustion of bituminous coal, presumably by coal ash (Czakiert and others, 2010, 2012). Jia and others (2009a) investigated the emissions of CO, SO_2 and NOx from combustion of subbituminous, bituminous coals and petroleum coke using an 100 kW oxy-CFB test rig. Limestone was added, O_2 concentrations as high as 60–70% and flue gas recycle levels of 50–60% were used. They found that in-bed sulphur capture rates were lower in oxy-firing mode compared to that in air-firing mode, leading to higher SO_2 emissions from oxy-combustion of bituminous coals. When combustion temperature increased from 850ºC to 950ºC, the SO_2 capture was improved resulting in a significant reduction in SO_2 emissions from oxy-combustion of petroleum coke. However, the effect of temperature on SO_2 emissions from oxy-firing of bituminous coals was not conclusively observed. Results from Alstom's 3 MWth oxy-CFB pilot-scale tests on coal and petroleum coke in air and O_2/CO_2 combustion mixtures containing up to 70% (volume) O_2 showed that when a bituminous coal was burnt in enriched O_2 at the normal temperature of 843º (1550ºF), the sulphur capture rate of limestone was 70–90% compared with >95% in air-firing of the same coal. For oxy-combustion of petroleum coke at 900ºC (1650ºF), the sulphur capture was 94–98%, comparable to the results obtained in air-firing (Nsakala and others, 2005). The pilot-scale oxy-CFB tests on a Spanish anthracite by FW found that at low furnace temperatures (<870ºC), the sulphur capture performance of limestone was reduced, and hence increase in limestone addition was needed to achieve the required SO_2 emission level (Hack and others, 2012a). Obviously, more work is needed in order to determine the optimum operating conditions for different types of coal in terms of SO_2 emissions control in oxy-CFB combustion.

NOx emissions from oxy-CFB combustion of coal are found, in general, to be lower compared with CFBC of coal in air (Levasseur and others, 2009; Czakiert and others, 2010; Nsakala and others, 2005; Jia and others, 2009a; Kuivalainen and others, 2009; Hack and others, 2012a). The lack of nitrogen in the combustion gas and the relatively low combustion temperature eliminate the formation of thermal NOx. The flue gas recirculation means that the NOx in the recycled gas is reburnt as it contacts the flame generated hydrocarbons and the reducing atmosphere near the flame resulting in reduced NOx emissions. In addition, it was reported that the inherently high concentration of H_2O under oxy-firing conditions resulted in a decrease in NOx formation but poorer SO_2 capture during oxy-CFB combustion of coal (Stewart and others, 2012).

The findings on CO formation under oxy-CFB combustion conditions are varied. Some studies found that CO emissions were higher in oxy-firing mode (Nsakala and others, 2005; Czakiert and others, 2012) while others reported that CO concentration was basically the same for air firing and oxy-CFB firing with flue gas recirculation (Jia and others, 2009a).

4.2.5 Bed agglomeration

Agglomeration is caused by compounds of various elements such as alkali metals (Na and K), alkali earth metals (Mg and Ca), sulphur, chlorine. Of these, alkali compounds play a critical role in bed agglomeration because some of the compounds have low melting points. With oxy-firing, the high local oxygen concentration near the oxygen injection points may increase the combustion rate resulting in higher surface temperatures. Some of the fuel particles may become hot enough for the fuel ash to become sticky or to melt which facilitates the agglomeration of the particles (Roy and others, 2011). This will be coal-specific, and likely to be more significant for low grade coals because some low rank coals contain relatively higher quantities of these elements.

Several studies have been carried out to investigate the agglomeration characteristics of coal in air-firing CFBC. However, there is limited research data available on this issue for oxy-CFB combustion of coal. Tests of bituminous coals and a petcoke on Alstom's bench- and pilot-scale (3 MWth) test facilities showed that there was no problem with bed agglomeration even with local oxygen concentrations up to 70% by volume (Levasseur and others, 2009; Morin, 2003). Roy and others (2011) used thermodynamic equilibrium modelling to predict the ash composition and formation of possible agglomerating compounds during oxy-CFB combustion of three Victorian (Australia) brown coals. They found that agglomeration was not a major problem during oxy-CFB combustion of the Victorian brown coals as long as the operating temperature was kept around 900ºC. Experiments in a oxy-CFB combustor were planned by the researchers to verify their prediction.

The recirculating flue gas through the boiler was also found to induce reburn and recapture of other pollutants. SO_3 can be reversibly converted back to SO_2 in the high temperature zone, which is then captured by sorbent. CO and VOC in the recirculation gas are primarily burnt out in the high temperature zone and will not cause any accumulation in circulation (Hack and others, 2010).

4.2.6 Sulphur sorbent utilisation efficiency

Limestone is often added to the fluid bed to capture the SO_2 formed during coal combustion. The sulphation reaction between SO_2 and limestone can proceed, depending on whether calcination of the limestone takes place under given reaction conditions, via two different routes:

indirect sulphation: $CaCO_3 \leftrightarrow CaO + CO_2$

$CaO + SO_2 + 0.5O_2 \leftrightarrow CaSO_4$

direct sulphation: $CaCO_3 + SO_2 + 0.5O_2 \leftrightarrow CaSO_4 + CO_2$

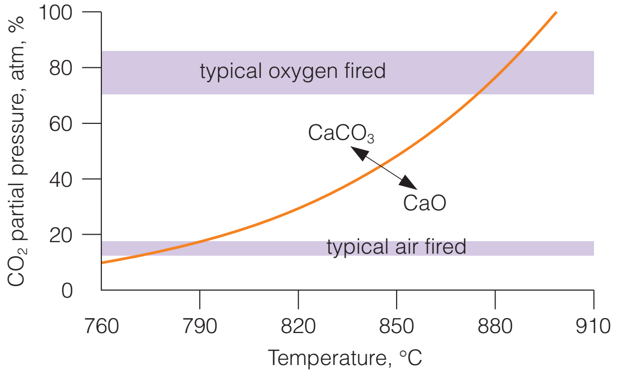


Figure 21 Equilibrium temperature of $CaCO_3$ calcination as a function of CO_2 partial pressure (Nsakala and others, 2005)

Figure 21 shows the temperature required to calcine the limestone as a function of the CO_2 content of the flue gas. With air firing, the CO_2 content of the flue gas is under 20%. Limestone will first be calcined to calcium oxide at around 800ºC, which is well below the typical CFB operating temperatures and therefore SO_2 is captured via indirect sulphation. With oxy-firing, however, the CO_2 content is above 70%. This requires a combustion temperature above 875ºC for calcination to occur. Consequently, the calcination of limestone might be hindered under typical oxy-CFB operating conditions

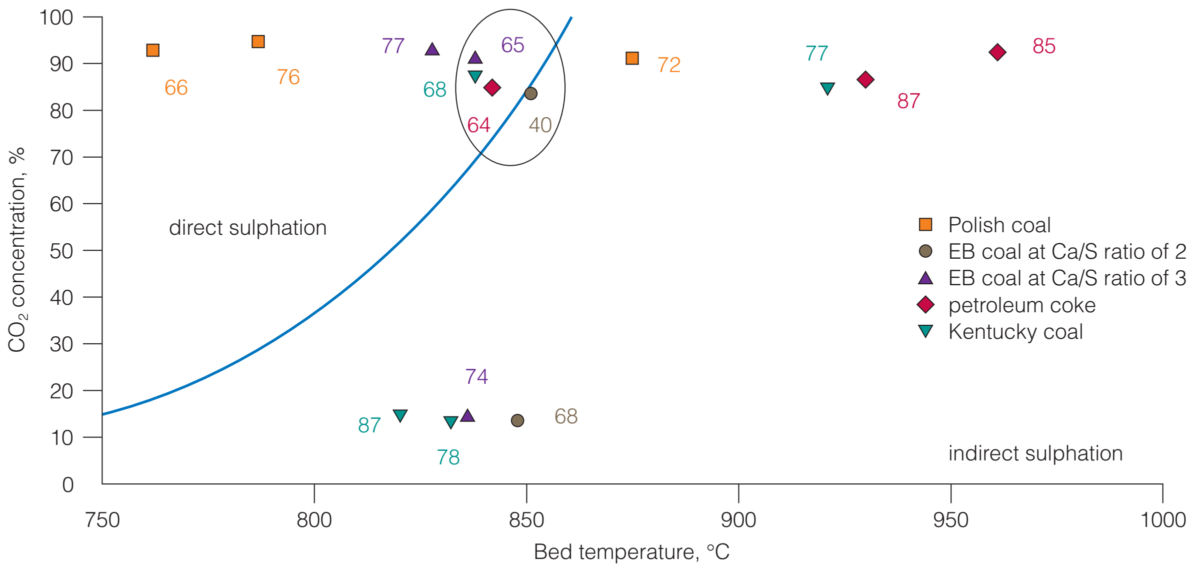


Figure 22 Sulphur capture reaction route and efficiency (numbers next to data points) (Wall and others, 2012)

(800–900ºC and CO_2 concentration around 80% or higher) and the sulphur be captured through direct sulphation route. In those locations such as the EHE and the convective pass where the temperature drops below the calcination temperature, the unreacted CaO may recarbonate (the reverse reaction) to form $CaCO_3$ (Wall and others, 2012; Nsakala and others, 2005).

Results from pilot tests on a Polish bituminous coal (the coal used at the 460 MWe Łagisza CFB power plant) showed that under oxy-firing conditions (24.1–29.2% O_2 concentration in feed gas, and 63–70% flue gas recirculation rate with Ca/S molar ratio of around 2), the indirect sulphation route was favoured at bed temperatures higher than 900ºC, whist at temperatures lower than 800ºC the direct sulphation reaction is predominant (Kuivalainen and others, 2009). The data in literature are, however, divided on the extent and route of sulphur capture under oxy-CFB conditions as illustrated in Figure 22. It was also found that the desulphurisation rate was similar under air- and oxy-firing at combustion temperature range of 860–910ºC. The direct sulphation resulted in a higher calcium utilisation efficiency compared to that of indirect sulphation (Kuivalainen and others, 2009). Garcia-Labiano and others (2011) reported that for the typical operating conditions and limestone particle sizes used in oxy-CFB combustion, the optimum limestone sorbent utilisation was achieved at temperatures of around 900ºC.

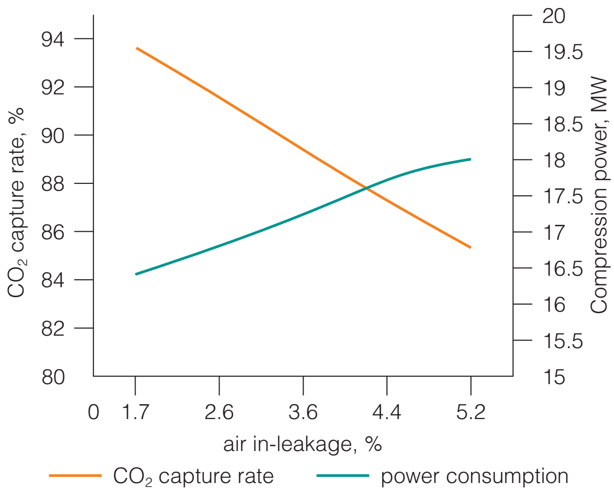


Figure 23 The effects of air ingress on CO_2 capture (Gasparini and others, 2012)

4.2.7 Air ingress

Air in-leakage will result in dilution of CO_2 in vent gas. Since the efficiency of CO_2 capture is highly dependent on CO_2 purity, air in-leakage into the boiler would penalise the efficiency of the CO_2 capture in terms of capture rate and power consumption as shown in Figure 23. Using Łagisza 460 MWe CFB power plant as a reference plant Eriksson and others (2007) studied the effects in air ingress on carbon capture using 3D CFB furnace modelling. They found that under oxy-combustion conditions with O_2 purity of 95 vol% and around 70.5% flue gas recirculation, 3 vol% of air in-leakage would reduce the CO_2 capture rate to 93.8%

compared to 98.1% of a sealed boiler. The power consumption of the carbon capture unit would increase by 4.1 MWe leading to a reduction in net plant efficiency (HHV based) by 0.5 percentage points. Apparently, sealing the oxy-CFB boiler in an adequate way to reduce air ingress can lower the CO_2 lost in the vent gas as well as the compression power. In particular, this is critical for retrofitting designs of existing power plants but also for new CFBC boilers.

4.2.8 Material

In oxy-fuel combustion, flue gas is recycled in order to control combustion temperature. Since the recycled flue gas contains mostly CO_2 and with air associated nitrogen being eliminated, the CO_2 and corresponding CO levels in the boiler are greatly increased. CO is a corrosive reducing gas and, with the recycled flue gas also containing corrosive gases such as SO_2 and HCl, corrosive conditions are expected to increase throughout the boiler as well as in localised furnace wall zones. Studies under taken by FW on oxy-fuel pulverised coal combustion showed that the CO and sulphur levels in boiler were higher under oxy-firing mode compared with air-firing mode. The maximum SO_2 levels in the superheater/reheater regions and the maximum H_2S levels along the furnace walls of the wall-fired boiler were observed to be about 50% higher under oxy-firing than air-firing. In the same studies, conventional materials used for boiler fabrication or tube and tube weld as well as materials that are under development were tested under varying conditions in both air- and oxy-firing mode using a laboratory electric furnace. The corrosion tests results showed that the effect of oxy-firing varied with the material, deposit, temperature, and gas composition (Robertson and others, 2012) and:
- wastage appeared to increase with increasing temperature, especially under strongly reducing conditions, but to decrease with increasing material chromium levels;
- the weld overlays used to protect the furnace walls of air-fired boilers from excessive corrosion appeared suitable for oxy-fired applications;
- no evidence of carburisation was found on the superheater/reheater tube materials.

In addition, with enriched O_2 in the oxidant gas the size of an oxy-CFB furnace is reduced compared to air-fired CFB of the same capacity, which may cause more serious abrasion of furnace wall. Therefore, the oxy-CFB has higher requirement for material. More work, especially tests on corrosion and abrasion of the materials exposed under oxy-firing operating conditions for a long period of time, is need.

4.3 Developments in oxy-CFB technology

4.3.1 R&D activities

There are several facilities from laboratory to pilot scale primarily in research centres and universities around the world that are engaged in developments on oxy-fuel technology. These are mainly used for fundamental study in various aspects, in particular, the combustion characteristics, emissions, in-bed sulphur capture, bed agglomeration under oxy-CFB combustion conditions. Researchers and engineers from universities, manufacturers and utility companies are involved in investigations and studies to gain better understanding of the fundamentals of oxy-fuel combustion, and to develop and validate oxy-fuel combustion based CFBC power plant concepts. Natural Resources Canada's CANMET Energy Technology Centre in Ottawa, Canada has a 0.1 and a 0.8 MWth CFB test rig with which tests on oxy-CFB combustion of bituminous and subbituminous coals have been carried out to validate the oxy-CFB process concept and to study air pollutants emissions under varying operating conditions. The data from these tests were used by FW in the development of its Flexi-Burn CFB technology (Jia and other, 2009a,b; Wall and others, 2012).

Study on operational impacts of variations in oxygen concentration, in-bed heat removal and external heat removal (from the solids recycle stream) during oxy-coal firing were performed by researchers at the Institute for Clean and Secure Energy (ICSE), University of Utah (USA) using a pilot-scale CFB test rig. Data were generated for use in the development and validation of a model, which would facilitate an understanding of the process dynamics during oxy-coal firing, and in particular, the impact of key process variables on bed temperature, bed agglomeration, solids recycle rate, and sulphur capture. In addition, the formation of SO_3 in the high CO_2 and O_2 environment of the oxy-CFB would be evaluated to develop an understanding of its potential for sulphuric acid condensation and corrosion (ICSE, 2012).

Research Centre for Energy Resources and Consumption (CIRCE) at University of Zaragoza, Spain co-ordinates the Project O2GEN, funded by the European Commission within the FP7, which investigates and demonstrates the integration of systems and equipment for CO_2 capture by means of oxy-firing. The objective of the project is to observe the combustion behaviour of low grade fuels in a fluidised bed under oxy-firing conditions using a 90 kWth CFB reactor. Secondary objectives include investigation of fouling, improving the characterisation of heat transfer, and studying the effect of secondary oxidising agents (air-stagging) with the aim of reducing the NOx and CO formation during the combustion. The influence of cofiring biomass with two low rank coals in an oxy-fuel FBC is also investigated (http://fcirce.es/).

Oxy-CFB combustion of lignite and bituminous coals using a 0.1 MWth CFB test facility was performed by researchers at Institute of Advanced Energy Technologies, Czestochowa University of Technology (Poland). The combustion behaviour of SOx, NOx, CO and CO_2 emissions from oxy-firing of the coals were investigated (Czakiert and other, 2010, 2012). Experimental studies and pilot-scale tests are also being carried out in research centres such as Technical Research Centre (VTT) of Finland, and universities in China, Europe and USA.

During September 2001 and October 2004, Alstom carried out a project called Greenhouse Gas Emissions Control by Oxygen Firing in Circulating Fluidised Bed Boilers, which was jointly sponsored by Alstom and the US Department of Energy (US DOE). In Phase I of the project, conceptual performance and economic analyses, and bench-scale oxy-FBC experiments on bed agglomeration and SO_2 capture were performed. The bench-scale testing done in a 10 centimetre (4 inch) FBC facility included fluid bed combustion fundamentals on two bituminous coals, two petcokes, and two limestones, in combustion mediums with oxygen concentrations as high as 70% by volume and bed temperatures ranging from 850ºC to 950ºC. In Phase II of the study, more than 300 hours pilot-scale testing of oxy-CFB concept and detailed combustion/bed dynamics evaluation using Alstom’s 3 MWth Multiuse Test Facility located at the Power Plant Laboratory in Windsor, CT, USA, were executed. The results were then used to update the oxy-CFB conceptual design, performance, and economics from Phase I. The oxy-CFB concept has been validated in both the bench- and pilot-scale tests. Alstom claimed that it was ready for the next step of large (100–350 MWe) oxy-fuel firing CCS demonstration plants (Marion and Nsakala, 2003; Jukkola and others, 2005; Levasseur and others, 2009). However, after years of bench- and pilot-scale development work and feasibility studies Alstom now appears to be inactive in the development of oxy-CFB technology.

Foster Wheeler (FW) has been developing an oxy-CFB combustion system called Flexi-Burn CFB since 2003. The process knowledge with design tools validation and development of models combined with high quality data are the key elements in designing a Flexi-Burn CFB boiler. In co-operation with the VTT, the Lappeenranta University of Technology (Finland) and CANMET (Canada), FW has been actively involved in bench- and pilot-scale tests on coal and petcoke under both air and oxygen firing conditions in order to gain better understanding of the oxy-CFB combustion process and to produce necessary data to extend modelling capabilities under those conditions. VTT has a 30–100 kW CFB combustor and it has been working with FW in developing CFBC technology for decades by conducting experimental work and developing modelling and design tools. FW used the 460 MWe SC CFB Łagisza power plant as a reference plant to study options of converting the CFB boiler for oxy-fuel combustion using its CFB boiler design and modelling tools.

FW is the technology provider and equipment supplier of the 30 MWth oxy-CFB boiler installed at the Fundación Ciudad de la Energía's (CIUDEN) Carbon Capture Technology Development Centre (TDC) in Spain. The principal focus for the CIUDEN Oxy-CFB demonstration project is to support and validate the scale-up of FW's Flexi-Burn CFB technology, which will be the basis for Endesa's Compostilla OxyCFB300 project. The OxyCFB300 commercial demonstration plant has already attracted EU funding of €180 million for pre-feasibility studies, with the intention of operating in 2015. The plant is aimed at producing 323 MWe electricity with a CO_2 capture rate of 91%. The investment decision was to be made at the end of 2012 (Wall and others, 2012) but by the time this report went to press no decision had been announced.

4.3.2 CIUDEN Oxy-CFB demonstration project

One of the current European R&D initiatives focusing on 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 carbon capture, transport and storage, thus contributing to the strengthening of the industrial and technological base in Spain and by extension in Europe (Lupion and others, 2011).

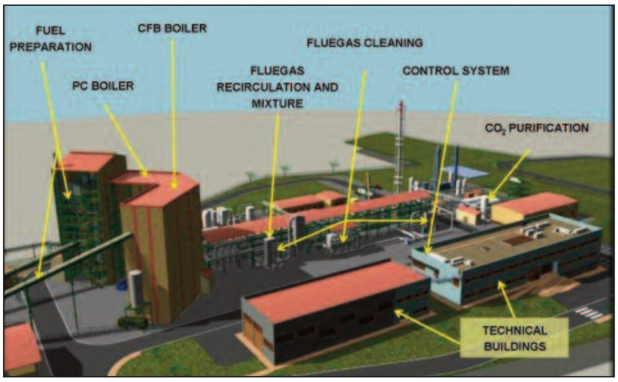


Figure 24 The CIUDEN TDC for CO_2 Capture (Hotta and others, 2011)

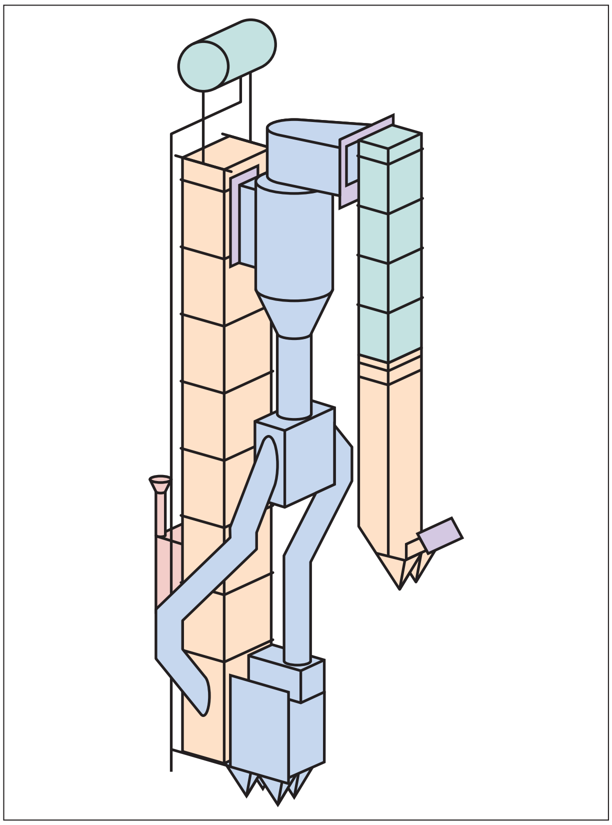
The CIUDEN TDC for CO_2 Capture is located in northwestern Spain, adjacent to the 1312 MWe Compostilla Power Station that is owned by ENDESA. As shown in Figure 24, it comprises two different technologies on oxy-fuel combustion: oxy-PC and oxy-CFB. It features all necessary equipment to provide the CO_2 stream ready for transport at a scale of 1:30. The CFB unit adopts FW's Flexi-Burn CFB technology with a design that allows different types of fuel and a wide range of operating conditions to be tested under both air and oxygen combustion mode. Anthracite, bituminous and subbituminous coals and petcoke are the design fuels for tests. The size of this experimental boiler is sufficient to allow the scaling of the results to commercial units while maintaining relatively low investment cost and operating expenses. Therefore, this installation provides a real basis for the design and operation of flexible and competitive oxy-CFB facilities at the demonstration scale thus accelerating the deployment of CCS technologies (Kuivalainen and others, 2010).

CFB boiler description

Figure 25 shows the main components and systems of the Flex-Burn CFB boiler at CIUDEN TDC. The CFB boiler is a natural circulation boiler in a balanced draft furnace with water cooled walls. With the given boiler size, the unit capacity is 15 MWth under air combustion mode whilst under oxy-firing conditions it is increased to 30 MWth. The main design parameters of the CFB unit are listed in Table 6.

To meet the particular requirements of a testing unit, the design of this CFB unit includes a wide range of measurement points and the option to vary the operating conditions with the maximum flexibility and versatility. Maintenance and inspection procedures of all unit components have been optimised, and the additional instrumentation, beyond what is normally included on a CFB, has been added in order to gather additional data from future operation.

The CFB boiler has a cooling system for solid material returning to the furnace in order to control the combustion temperature, a solid separator for the recirculation of bed material, an ash sealing-direction device, a heat recovery area and an economiser. The CFB unit will provide the opportunity for testing in-bed removal technologies such as the addition of limestone in order to reduce the concentration of the SO_2. It also includes provisions for selective non-catalytic reduction (SNCR) of NOx (with injection of ammonia into the cyclone) and combustion oxidant staging for NOx emissions control, as well as fly ash reinjection (Hack and others, 2012b; Alvarez and others, 2011).



CFB boiler

- furnace with primary air plenum and secondary air nozzles;
- fluid bed heat exchanger (INTREX™ superheater);
- solids separator (cyclone);
- loop seal for bed material circulation to fluid bed cooler and furnace;
- bed material return duct to the furnace;
- bed material return duct to the cooler;
- steam-cooled walls with convective evaporator bank;
- economiser.

Main systems:

- flue gas recirculation, oxygen mixing and pre-heating for oxidant preparation*
- fuel feed, limestone, sand and ammonia feed systems;
- fly ash recycling;
- ammonia feeding;
- bottom ash extraction and cooling;
- flue gas cleaning*
- CO_2 compression and purification unit*
- DCS (shared with other test units)
- auxiliary services*

* shared with PC boiler

Figure 25 The main components and systems of CIUDEN TDC's CFB boiler (Hack and others, 2012b; Kuivalainen and others, 2010)

The fuel flexibility of the CFB boiler allows the utilisation of a wide range of coals to be burnt individually or be cofired with biomass fuels. More detailed description of the facilities at CIUDEN TDC has been reported (Lupion and others, 2011; Hack and others, 2011).

Testing programme

The objectives of the CIUDEN R&D demonstration project are to validate the full chain of CCS technologies and to acquire the data for scaling-up both the oxy-PC and oxy-CFB units. A specific testing campaign has been designed considering the wide range of possibilities of the plant. The oxy-CFB testing programme is focused on the development and demonstration of a power plant concept based on CFBC technology combined with CCS. It aims to (Alvarez and others, 2011):

- demonstrate oxy-fuel combustion in a 30 MWth CFB boiler;
- generate data for model validation;
- generate the knowledge base for scaling-up;
- determine the optimum operating parameters to allow sizing of new full-scale oxy-fired units;
- obtain data on the combustion behaviour of different coals in air- and oxy-firing conditions;
- compare the performance between air- and oxy-firing modes in order to be able to relate the air combustion experience to oxy-firing conditions;
- when operating in air mode, provide the flue gas stream for testing and demonstration of post-combustion carbon capture equipment;
- when operating in oxygen combustion mode, provide a rich CO_2 gas stream for the testing of process equipment used for CO_2 purification and compression;
- obtain data to evaluate the impact that oxygen combustion might have on the combustion, emissions and on radiant and convective boiler heating surfaces.

The preliminary test programs have been designed to investigate the effects of the following parameters (Hack and others, 2011):

- bed temperature at low, medium and high level;
- excess O_2 concentration;
- O_2 concentration;
- fluidisation velocity;
- flue gas recycle flow;
- sorbent at the bed;
- bed inventory: normal or high;
- pollutant emissions as a result of varying operating conditions;
- SO_2 abatement;
- corrosion, fouling, agglomeration.

Table 6 The main features of CIUDEN TDC's CFB boiler (Hack and others, 2012b)

Furnace dimensions (height/width/depth) (metres)	20 x 2.9 x 1.7
Capacity, MWth	15 (under air combustion mode)
	30 (under oxy-firing mode)
Maximum steam flow, t/h	47.5
Superheated steam temperature, °C	250
Superheated steam pressure, MPa	3
Feedwater temperature, °C	170
Outlet boiler flue gases temperature, °C	350–425
Oxygen consumption, kg/h	8775
Flue gas recirculation, kg/h	25,532
Coal consumption, kg/h	5469
Limestone consumption, kg/h	720

Table 7 The main characteristics of the design fuels for the CIUDEN CFB tests (Kuivalainen and others, 2010)

	Anthracite	Bituminous	Subbituminous	Petcoke
Proximate analysis (as received, wet basis), %				
Moisture	8.84	7.52	26.75	6.84
Volatile	6.47	22.30	36.78	10.60
Ash	32.00	13.84	1.49	0.82
Fixed carbon	52.69	56.35	34.98	81.80
Ultimate analysis (as received), %				
C	52.59	65.06	52.66	79.82
H	1.68	3.37	3.76	3.93
N	0.88	1.65	0.66	1.78
S	1.07	0.38	0.09	5.11
O	2.95	8.24	14.59	1.70
Higher heating value, MJ/kg				
	19.8	27.4	20.7	32.6

Coals of varying quality, a petcoke as well as co-combustion of the coals with biomass are to be tested. The main characteristics of the design fuels are shown in Table 7.

Initial tests results

The CIUDEN CFB unit was commissioned and was first fired with coal in September 2011. The functionality test runs were conducted during the first half of 2012 and integrated operational tests with CPU were scheduled for later in 2012. More tests have been planned for the period of 2012 to 2013. The unit has been run successfully in both air and oxygen combustion mode. The first tests in this CFB boiler were carried out burning in air a Spanish anthracite coal. Data recorded from the various process parameters such as bed temperature and unburnt carbon were in line with expectations. The CFB boiler reached full load in a stable manner and the auxiliary equipment ran successfully under varying operational conditions.

The operation of the oxy-CFB boiler including switching between air and oxygen modes was demonstrated during the first quarter of 2012. Calcitic limestone was used as sulphur sorbent. During the preliminary testing, the process variables had been steam load, combustion temperature, limestone feed rate and oxygen content in oxidant streams. It was demonstrated that the transition between air- and oxy-mode was smooth and uncomplicated. A minimum of 80% (dry volume) CO_2 level in flue gas could be achieved. This level of CO_2 corresponds to an air in-leakage of approximately 3%.

The initial test results showed that SO_2 emissions below 200 mg/m^3 could be readily achieved in oxy-firing mode by feeding limestone at a feed rate of 10% of the fuel feed. The tests also confirmed the results of the smaller pilot tests performed earlier, which showed that the SO_2 capture was temperature-dependent. At furnace temperatures lower than 870ºC, the capture performance was reduced and thereby requiring more limestone to achieve the required SO_2 emission level. This confirms that SO_2 capture occurs via a direct sulphation mechanism. The results also showed that NOx emissions were lower in oxy-firing mode compared to air combustion mode, which was consistent with previous small pilot test results (Hack and other, 2012a,b).

4.3.3 The OXYCFB300 Compostilla Demonstration Project

The OXYCFB300 Compostilla Project is one of the six selected CCS EU demonstration projects co-funded by the European Energy Programme for Recovery (EEPR) of the European Commission. The Project is a consortium of three partners: (1) Endesa Generacion, co-ordinator of the Project and owner of the Compostilla Power Station which is the site of the 300 MWe OXYCFB300 Demonstration Plant; (2) CIUDEN; and (3) Foster Wheeler, the technological provider of the CFB unit at the CIUDEN TPC. The overall Compostilla Project is based on a future 330 MWe SC oxy-CFB plant, with 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 commercial scale for a wide range of fuels: raw coals, petcoke, and biomass (Lupion and others, 2011; Hotta and others, 2011). The main features of the Project are shown in Table 8.

Table 8 The main features of the OXYCFB300 Compostilla Demonstration Project (Hotta and others, 2011)

Capture technology	330 MWe OXY-CFB supercritical boiler
	wide design fuel range (domestic and imported), including biomass
CO_2 transport	30.5–40.5 cm underground pipeline; 150 km
	5500 t/d; approximately 12 MPa
CO_2 storage	deep geological formation

The Project is composed of two phases (Lupion and others, 2011):

- Phase I – Technology Development (2009-12): this phase includes the construction of three Technology Development Plants (TDPs) at pilot scale: CO_2 capture and transport TDPs at CIUDEN TDC, and the storage TDP in Hontomin (Burgos, Spain). These activities aim to provide the project with valuable experience and technical support for Phase II. This phase also includes the survey and geological characterisation of a safe and suitable geological CO_2 storage for all the demonstration plant lifetime, development of the Project FEED including the plant, pipeline and the injection infrastructure, the permitting process, and the associated engineering studies required to guarantee the successful delivery of Phase II.
- Phase II – Construction of the Demonstration Project Infrastructure (2013-15): the Final Investment Decision process of the integrated Project would start by mid-2012, based on the knowledge and results obtained from Phase I, and the final permitting, financial and economical boundary conditions of the Project, that must converge with positive results before Phase II would be approved to go ahead. Phase II includes the construction of a 300 MWe SC oxy-CFB demonstration plant at the Compostilla site together with the corresponding CO_2 transport and storage infrastructure. The reason for adopting this staged approach to implementation (pilot-scale TDP followed by large-scale Demo Plant) is to significantly reduce the potential for economic and technical challenges that could arise during the Demo Plant phase of the Project. No decisions has been announced yet.

The test results from CIUDEN's demonstration unit will be used to validate the design of the Project's 300 MWe SC oxy-CFB boiler.

Comments

The Oxy-Coal Alliance was recently formed consisting of Praxair, Foster Wheeler, and other commercial and governmental organisations. The Alliance announced plans to build a 50 MWe oxy-CFB power generating unit integrated with CO_2 capture and storage for Jamestown Board of Public Utilities in New York (USA). The FW's Flexi-Burn CFB technology would be adopted. This commercial project aimed to demonstrate the viability of the technology and provide design data for scaling up to units of 500 MWe (Victor and others, 2009). However, the project did not receive funding from US DOE and its future is now uncertain. Therefore, the OXYCFB300 Compostilla Demonstration Project appears to be the only oxy-CFB technology R&D demonstration project that is being actively pursued at the moment.

4.4 Performance and costs

4.4.1 Performance

From the fundamental studies and small-scale tests having been executed so far, it can be concluded that oxy-CFB technology can be readily developed using conventional CFB boiler technology. In terms of operation, bed agglomeration is not a major issue for a properly designed oxy-CFB boiler even with local oxygen concentrations up to 70% by volume. In-furnace heat transfer coefficients for oxy-firing are comparable to air firing because the bed temperature can be controlled by recirculation of cooled solid. The convection pass heat transfer coefficients are higher with oxygen firing than with air firing, as expected. SO_2 capture by lime/limestone in an oxy-CFB boiler occurs mostly via direct sulphation route. No significant changes seem to occur in emission levels of SO_2 and NOx. The emissions of mercury, volatile organic compounds (VOC) and other trace elements with oxy-firing are at least as low as with air-firing, whilst CO emissions increase somewhat with oxygen firing, due to high CO_2 partial pressure in the flue gas. Unburnt carbon in ash with O_2 firing is comparable to that with air firing.

The power output of an oxy-CFB power generating unit will be lower compared with a corresponding air-firing CFB unit due to the additional auxiliary power consumption by ASU and CPU units. Other

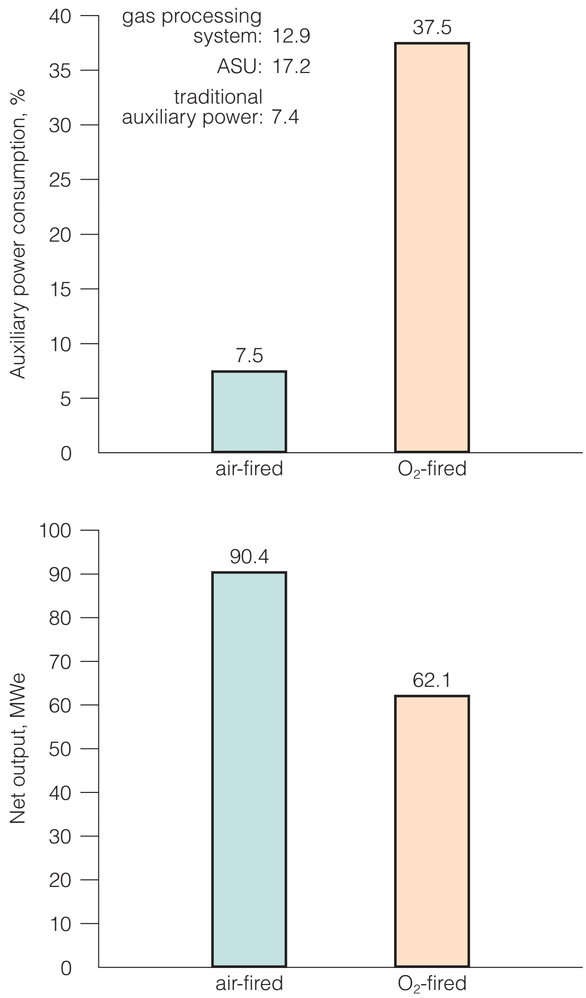


Figure 26 The plant auxiliary power consumption and net plant output comparison for CFB (Wall and Yu, 2009)

auxiliary power consumption is close to that in air firing. In general, the efficiency penalty is about 10 percentage points in oxy-CFB operation compared to air-firing. An overall plant performance comparison for 210 MWe oxy- and air-fired CFB plant (with steam cycle of 12.4 MPa/538ºC/538ºC and many other common ground) showed that they produced net plant thermal efficiencies of 26.0% and 35.5% (HHV based) respectively (Jukkola and others, 2005). The plant auxiliary power consumption and net plant output of a CFBC power generating unit in O_2 and air combustion mode are compared in Figure 26. CO_2 emission from air-fired CFB plant without carbon capture is 0.91 kg/kWh whilst the CO_2 released from the oxy-CFB plant with 90% of carbon capture is 0.077 kg/kWh (Nsakala and others, 2005).

Similar findings were also obtained in a recent independent assessment of the cost and performance of low-rank coal oxy-fuel combustion power systems (NETL, 2010). For a SC CFBC power plant with steam conditions of 24.1 MPa/593ºC/593ºC and a net power output of 550 MWe, the estimated gross and net power outputs as well as the net plant efficiencies of the CFBC plant operating under air and oxygen combustion mode burning Powder River Basin (PRB) subbituminous coal and Beulah-Zap lignite coal are compared in Figure 27. The difference between the gross and net power output represents the auxiliary power consumption of the plant. It can be seen from Figure 27 that the net plant efficiencies decreased by around 9 percentage points in oxy-firing cases due to the energy penalty paid to accomplish 90% CO_2 capture and sequestration.

Comments

The ASU is the biggest additional power consumer in the oxy-combustion system. Cryogenic air separation is the only technology available in the scale required for the utility-sized oxy-CFB boilers. The specific energy consumption decreases with plant size. Optimisation of the systems for the oxy-fuel combustion needs such as O_2 purity and pressure offers potential for energy savings. On the other hand, significant improvement of the electrical efficiency could be attainable if less energy-intensive technology for the air separation were ready to deploy at commercial scale (Gasparini and others, 2012). New technologies, such as Oxygen Transport Membrane (OTM), are being developed to separate oxygen from air using much less energy (Nsakala and others, 2005).

The CPU is the second biggest additional power consumer in the oxy-combustion system. It is based on existing gas processing technologies with limited potential for efficiency improvements. The CPU energy needs may decrease indirectly if the extent of gas clean-up is reduced. Reduction of non-condensable gases in the flue gas could become possible through improved process knowledge such as less excess oxidant and equipment design development like properly sealed boiler with low level of air ingress. Also, relaxing gas quality specifications related to transport and storage would reduce the relevant penalty (Gasparini and others, 2012).

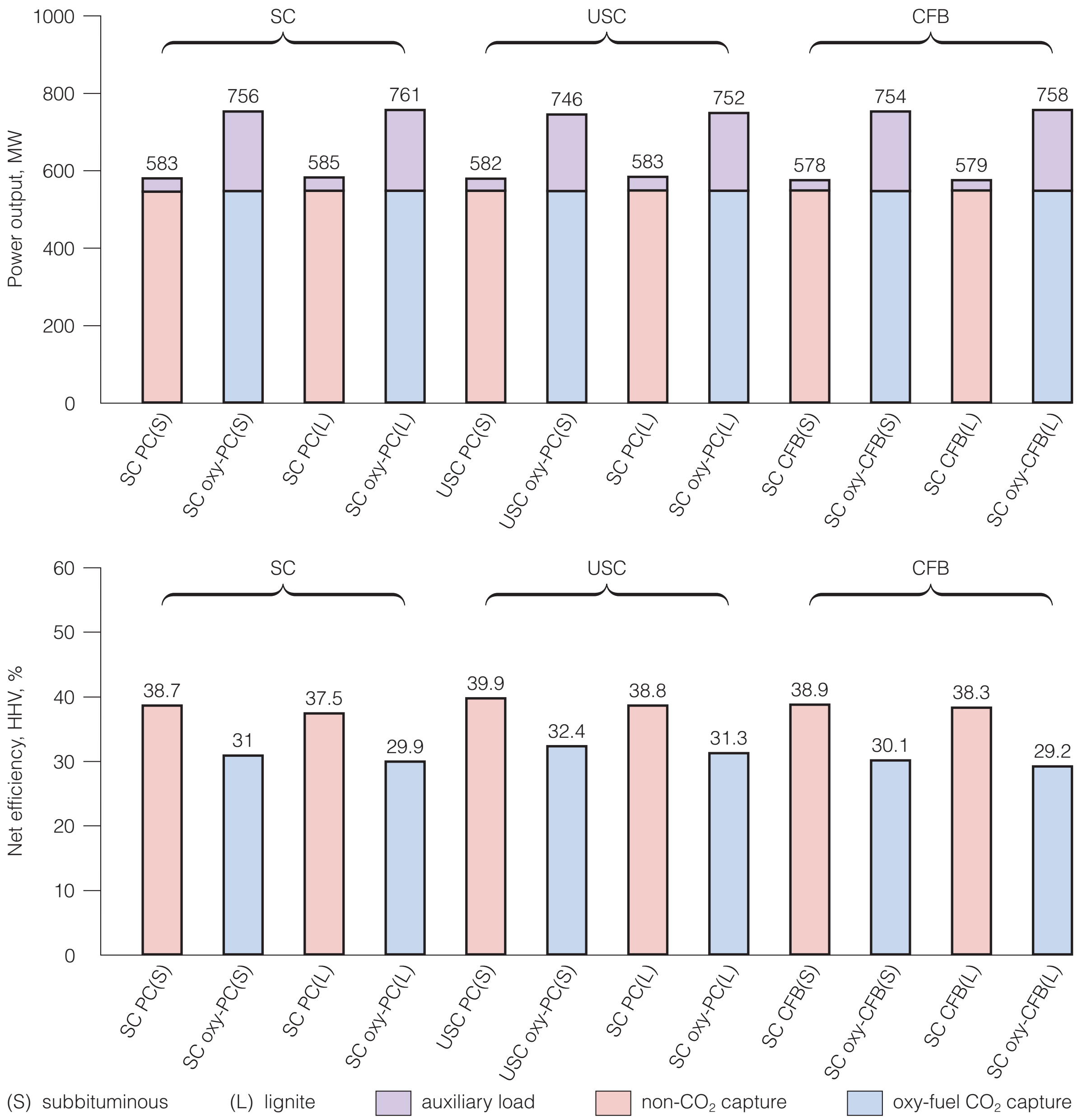


Figure 27 Comparisons of power consumption and efficiencies of a 550 MWe (net) SC CFBC power plant in air and O_2 firing mode (NETL, 2010)

It is possible to recover to a certain degree the lost efficiency by exploiting the extra waste heat available in oxy-firing case. For example, with an oxy-CFB CHP (combined heat and power) plant, integrated recovery and utilisation for district heating purposes of the waste heat from steam cycle and the flue gas process units can improve the overall plant efficiency.

4.4.2 Costs

Due to the reduced gas flow with oxygen firing, much of the equipment in the boiler island (such as combustor, cyclones, backpass heat exchangers, air heater, fans, ductwork and dust collection devices) is smaller. As illustrated in Figure 28, a 210 MWe oxy-CFB unit operating with a 70% O_2 concentration occupies approximately 51% of the plan area and has about 56% of the volume of a corresponding 210 MWe air-fired CFBC unit. The total boiler weight of the oxy-CFB is about 65% of the air-fired unit. This results in a boiler cost around 32% less than an air-fired CFB boiler (Nsakala and others, 2005).

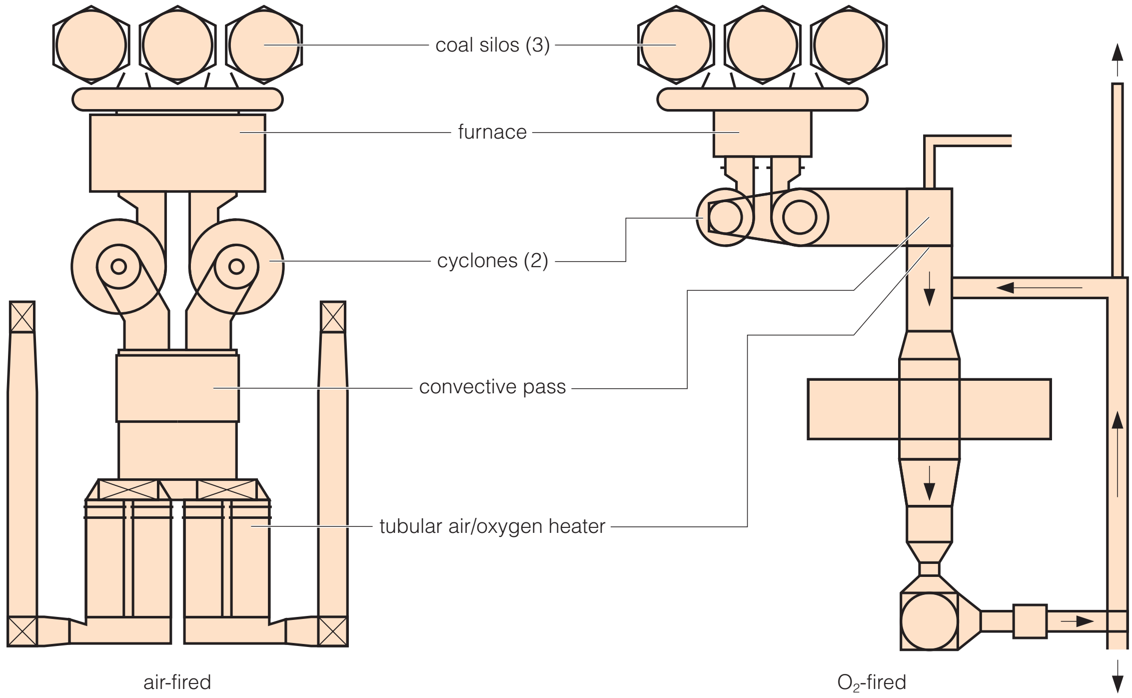


Figure 28 Comparison of the plan views of 210 MWe oxy-fired and air-fired CFB plant (Nsakala and others, 2005)

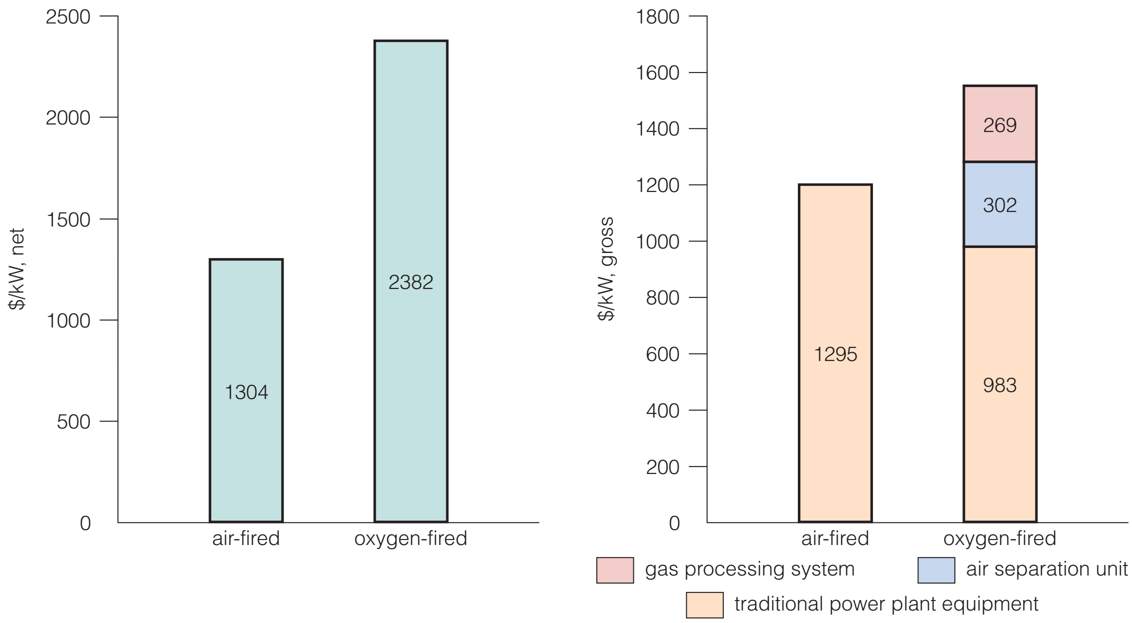


Figure 29 Comparisons of the total plant investment costs of the 210 MWe air- and O_2-fired CFBC plants (Jukkola and others, 2005)

The relatively costly and power consuming ASU and CPU systems have a major impact on the capital and operating costs of an oxy-CFB plant. Figure 29 compares the estimated total plant investment costs of the 210 MWe air and O_2 fired CFBC plant in terms of the costs in US dollars for per unit (net and gross) electricity produced. It can be seen from Figure 29 that the specific cost ($/kW-net) of the oxy-CFB plant is over 80% higher compared to that of the air fired CFBC plant without CO_2 capture. The figure also shows that there is around 20% cost savings (in $/kW-gross) for the traditional power plant components as a result of oxygen firing (Jukkola and others, 2005; Nsakala and others, 2005). This is primarily a result of the cost reductions in the boiler island for equipment due to the reduced gas flow with oxygen firing as discussed above.

The corresponding levelised cost of electricity (COE) values for the 210 MWe air- and O_2-fired CFBC power plant are 45 \$/MWh and 79 \$/MWh, respectively, as shown in Figure 30 (assume that CO_2 credits are not available). This represents a nearly 76% increase in COE when operating the CFBC plant in oxy-firing mode with CO_2 capture. The operating and maintenance costs of the oxy-CFB plant are more than doubled compared to those of the corresponding air fired CFB power plant. The carbon mitigation cost is the additional cost of electricity divided by the reduction in CO_2 emissions. In this case, the CO_2 mitigation cost of the oxy-CFB plant is approximately 37 \$/t of CO_2 avoided. (Jukkola and others, 2005; Nsakala and others, 2005).

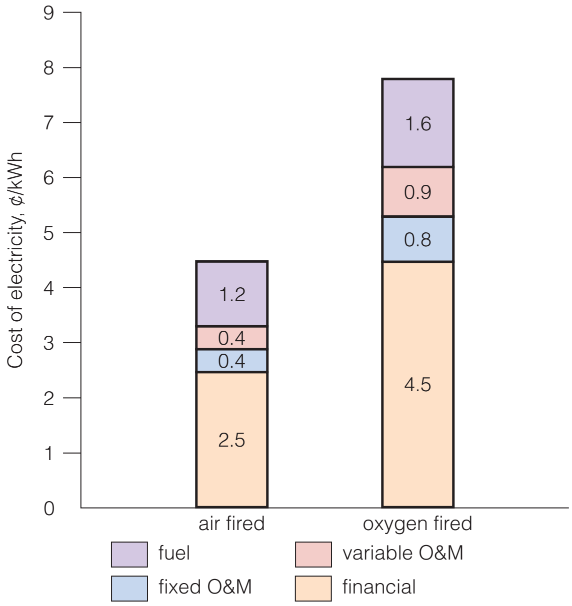


Figure 30 Comparison of COE of the 210 MWe air- and O_2-fired CFBC plants (Jukkola and others, 2005)

In 2008, Vattenfall in co-operation with FW and Praxair conducted a conceptual design study and detailed process simulations for a hard coal fired oxy-CFB combined heat and power (CHP) plant. Conditions representative of a plant in Hamburg were applied as design basis of a commercial-scale CFB plant with size of 500 MWe (gross) and 0–400 MWth of district heating (DH). For the economical evaluation, the following assumptions were made:

- annual operating time: 7500 hours;
- interest rate: 6%;
- plant operating life: 25 years;
- coal price: 6.6 €/MWh;
- district heating credit: 25 €/MWh;
- all investment costs were reported on a ±30% level;
- no cost for CO_2 transportation and storage included.

The cost and performance evaluation results, as shown in Table 9, are consistent with those reported by others as discussed above. The results also demonstrated that the inclusion of district heating generation can significantly improve plant economics (Simonsson and others, 2009).

Table 9 Cost and performance comparison of CFBC power plants in air-/O_2-firing mode with and without DH (Simonsson and others, 2009)

	Air-CFB (condensing)	Air-CFB (district heating)	Oxy-CFB (condensing)	Oxy-CFB (district heating)
Fuel input, MWth	1051.7	1051.7	1046.7	1046.7
Net power output, MWe	472.2	435.4	381.0	347.1
District heating output, MWth		268.8		268.8
Net electric efficiency, %	44.9	41.4	36.4	33.2
CO_2 emissions, kg/MWh	742	806	62	68
Specific investment, €/kWe net)	1621	1703	2952	3096
COE, €/MWh	38.8	28.1	65.6	52.7
CO_2 avoidance cost, €/tCO_2			37.9	33.4

4.5 Oxy-PC versus oxy-CFB

Competition between oxy-PC and oxy-CFB is similar to that between air fired PC and CFB power plant. An oxy-CFB system has all the advantages of the CFBC technology such as fuel flexibility, good load-following capacity, possibility to meet SOx and NOx emission requirements without additional flue gas cleaning equipment and simpler fuel feeding system. Compared with oxy-PC, oxy-CFB technology has additional advantages including the following (Wall and others, 2012):

- reduction of unit size: the recirculation of the cooled solids from the external heat exchanger allows an oxy-CFB boiler to operate with lower flue gas recirculation rate compared to oxy-PC systems. Reduction of flue gas recycling leads to reduced size of the boiler island and some of the auxiliaries consumption, potentially allowing more compact and less expensive oxy-CFB boilers;
- easier transition between air- and O_2-firing mode: transition from air to oxygen combustion is potentially easier relative to oxy-PC because oxy-CFB has large amount of inert bed material that also helps in controlling the bed temperature;
- simple implementation: relative to oxy-PC, oxy-CFBs do not need new, sophisticated burner design and management;
- ability to burn low-reactive fuel: the strong mixing in the furnace and long residence time due to recirculation of solids allow a good carbon burnout; this clearly suits low-reactive coals;
- reduced air ingress: large part of furnace operates at positive pressure so the air in-leakage is low (potentially 1% for an oxy-CFB boiler compared to possibly 5% for an oxy-PC boiler);
- lower excess O_2: lower excess O_2 means that the required oxygen supply is reduced leading to increased CO_2 recovery and reduced energy penalty.

As with air-fired systems, ash produced by oxy-CFB boilers could be an area of concern. CFBC ashes generally do not fit into the standards developed for PCC ashes although ashes from some of the existing CFBC plants are being reused in different applications. The costs of ash disposal could have an impact on oxy-CFB power plant economics.

The cost structure of oxy-PC and oxy-CFB plants is similar as for both technologies the major cost increases are due to the ASU and CPU units. A study carried out in 2006 by Alstom, Electricité de France (EDF) and the Technical University of Compiègne (UTC) compared various advanced coal-based power plant designs with CCS. The comparison between new oxy-CFB and oxy-PC power plant was made based on Alstom's 600 MWe (gross) SC CFB design with steam cycle of 29 MPa/615ºC/635ºC and oxygen concentration of 70%. The study found that large oxy-CFBs could potentially be 10% cheaper than oxy-PC power plants (Jaud, 2009).

In the recent study, mentioned in Section 4.4.1, researchers at the US DOE National Energy Technology Laboratory (NETL, 2010) assessed the cost and performance of low-rank coal-fired oxy-PC and oxy-CFB power plants with 90% CO_2 capture. A consistent technical and economic approach was used in order to accurately reflect current market conditions for plants starting operation in 2015. In all cases, the feed rate for PRB subbituminous and Beulah-Zap lignite coal was adjusted to maintain a nominal net plant output of 550 MWe for the SC/USC oxy-PC and SC oxy-CFB power plants. The steam conditions of 24.1 MPa/593ºC/593ºC and 27.6 MPa/649ºC/649ºC were assumed for the supercritical and ultra-supercritical steam cycle, respectively. The results of the NETL study are shown in Figure 31 and as illustrated in the figure the estimated total plant costs (with contingencies) of oxy-CFB plants were higher than those of oxy-PC plants. For example, the total plant costs for subbituminous coal fired SC oxy-CFB were 3491 $/kW, compared to 3093 $/kW for SC oxy-PC and 3175 $/kW for USC oxy-PC plants. The higher costs for oxy-CFB were attributable to higher process contingencies applied to account for the fact that SC CFBC of this size had not been commercially demonstrated. The 20-year levelised COE for SC oxy-CFB burning subbituminous and lignite coal was 0.1107 $/kWh and 0.1204 $/kWh, respectively. The COE for SC oxy-PC was 0.0998 $/kWh for burning subbituminous coal and 0.1060 $/kWh for lignite, whilst the COE for USC oxy-PC was 0.1013 $/kWh for subbituminous coal firing and 0.1129 $/kWh for lignite firing (NETL, 2010).

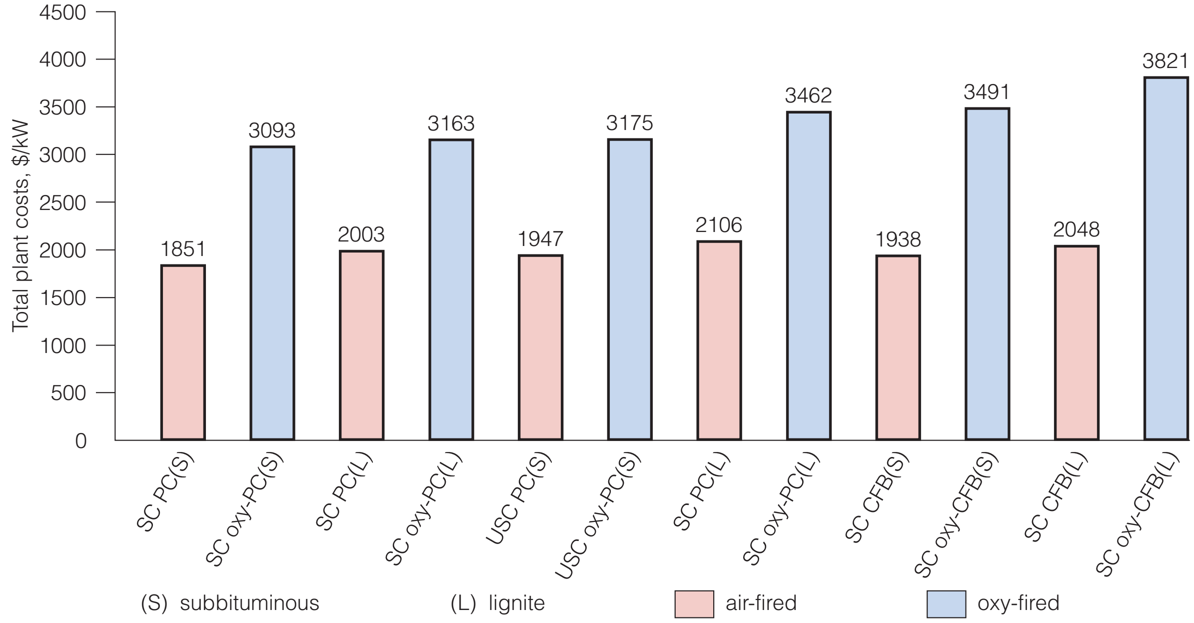


Figure 31 Estimated total plant costs for oxy-fuel combustion power plants (including contingencies but excluding CO_2 transport, storage and monitoring costs) (NETL, 2010)

The NETL study did not consider any in-bed sulphur capture. Instead, a downstream desulphurisation system using Alstom's Flash Drying Absorber (FDA) coupled with a fabric filter unit was studied. For oxy-CFB plants where in-furnace sulphur capture is sufficient to meet the emission standards and no downstream desulphurisation system is required, the cost and energy penalty will be reduced. In addition, as operational experience is gained from the Łagisza 460 MWe SC CFBC power plant, the 550 MWe SC CFBC units at Samcheok power plant, and the CIUDEN project, the total costs and COE for oxy-CFB plants are expected to decrease.

In summary, oxy-CFB is less developed compared to oxy-PC in terms of technology development. However, oxy-CFB technology is developing rapidly. Oxy-CFB system has several advantages over oxy-PC plants. Current knowledge indicates that the costs of a mature oxy-CFB technology is likely to be of the same order for the oxy-PC technology. At the very least, for low sulphur or lower grade coals, oxy-CFB may be a real competitor to oxy-PC both technically and economically.

5 Conclusions

Since its first application in power generation in 1985, coal-fired power plants using CFBC technology can now be found in the USA, Europe, Japan, China and other parts of the world. However, the deployment of CFBC technology in power generation industry has been limited due to its relatively small unit size and the use of subcritical steam conditions.

CFBC technology has been evolving continuously and significant technical developments and engineering design optimisations have been achieved.

5.1 The status of the CFBC technology

Modern large SC CFB boilers have performance and economics comparable to corresponding PCC boilers while offering greater fuel flexibility.

Operational performance

A major advantage of CFBC technology is its ability to consume all types of coals, coal wastes and a wide variety of other fuels alternatively or simultaneously. The strong mixing and long residence time in the furnace means that CFBC boilers have high combustion efficiencies (up to >99%). The emerging large SC CFBC units can achieve a net plant efficiency of 43% (LHV basis) or higher. A CFBC system offers operational flexibility and good load-following capability but is not well suited for on-off cycling. Today, CFBC boilers can achieve an average availability of 90% or higher.

Environmental performance

Another main advantage of a CFBC boiler is the low emissions of NOx and SO_2 due to the low combustion temperature of a CFBC boiler resulting in a considerably reduction in NOx formation, and the in-bed SO_2 capture by limestone. NOx emissions of less than 200 mg/m^3 and >95% of sulphur capture as well as particulate emissions of 20–50 mg/m^3 can be achieved with a modern CFBC plant.

Plant size and steam conditions

Almost all the existing coal-fired CFBC power plants are relatively small in size and use subcritical steam cycles. However, significant advances in CFBC technology have been achieved in scaling-up CFBC boilers and adopting supercritical steam cycles. Today, SC CFBC boilers with capacities of up to 800 MWe are offered to the commercial market with steam conditions of around 25 MPa/600ºC/600ºC.

Applications

CFBC technology is widely applied in chemical plants, steel work, utility and other industrial processes. Today, approximately 600 coal-burning CFBC power generating units with capacity of >46 GWe have been installed and are in operation worldwide, and nearly 180 units with a total capacity of over 26 GWe are currently under construction or planned to be built (Platts, 2012).

5.2 Recent developments in CFBC technology

Furnace design

Proper design of the furnace is key to the successful and efficient operation of a CFBC boiler. Due to the nature of fluidised-bed combustion, there is a limit to the height and depth of a CFBC furnace. Different approaches are taken to overcome the limitation to furnace dimensions when scaling-up. Alstom has adopted, for large CFBC, pant-leg design furnaces whilst Foster Wheeler's large CFBC furnace has one single fluidising grid. The tapered lower furnace design is adopted by major CFBC boiler manufacturers such as FW and Alstom. The innovative and optimised designs enable the manufacturers to increase the size of CFBC boilers while ensure good mixing of bed material and air in the furnace and the required combustion efficiencies.

Solid separation systems

Cyclones are the most commonly used solid separation system in CFBC boilers. The development of water- or steam-cooled cyclones and the improved cooled-cyclone design have minimised the refractory use and reduced the maintenance and operating costs leading to CFBC boilers with longer service life and higher availability. To improve the efficiency and to reduce the physical size of the CFBC's solid separation systems, a number of optimised or novel designs have been developed over the years. FW introduced a Compact Separator that uses pentagonal shaped membrane water walls with a thin layer of refractory inside the separator to smooth out the corners. This design eliminates the need for expansion joints and therefore increases the availability, and reduces the footprint of the boiler. Other solid separation systems with novel designs such as water-cooled square cyclones, louvre-type separators (staged CFBC boiler) and down-exhaust cyclone separators (Π-shaped CFBC boiler) are under development.

For smaller CFBC boilers, impact separators such as B&W's two-stage solids separation system is also used. For large CFBC boilers, scaling-up issues are reduced by using cyclones of a proven size and design, and an optimised arrangement of the cyclones are used.

External heat exchangers

For CFBC boilers larger than 300 MWe and with reheat, it may not be possible to perform all the required heat duty in the furnace and backpass so for larger boilers external heat exchangers (EHE) are added to provide additional heat duty. A bubbling fluidised bed is normally used for EHE due to its relatively high heat transfer rate, to extract heat from the hot circulating bed material that is collected by the solid separators. The use of EHE enables the superheat and reheat steam temperatures to be adjusted, and the combustion temperature to be controlled. By standardising tube bundle arrangements and by utilising a modular approach, scaling-up the unit size can be accommodated without developing new EHE designs. Therefore, with increasing boiler size, the number of EHEs is increased to match the number of cyclones.

The CFBC boilers by Alstom and AE&E Lentjes GmbH usually feature pant-leg design with EHEs. FW developed an improved EHE design called integrated recycle heat exchanger (INTREX™), which integrates the heat exchanger waterwall with the furnace water-steam system and the return channel. The advantages of INTREX™ include reduced maintenance and increased operational flexibility.

Scaling-up

Over the last ten years, one of the significant advances of CFBC technology has been the increase in the capacity of CFBC boilers. The world largest coal-fired SC CFBC power generating unit which started operation in 2009 has a capacity of 460 MWe. More coal-fired SC CFBC power plants with unit sizes of 550 and 600 MWe are under construction or under commissioning in South Korea and China. FW has developed a modular design approach allowing it to offer commercial 600 MWe and 800 MWe SC units. Further scale-up of CFBC units to above 800 MWe is possible.

Advanced steam cycle with once-through boiler technology

To move CFBC technology to advanced steam cycle conditions, once-through boiler technology has been adopted in the designs of SC CFBC boilers. The SC CFB unit at Łagisza power plant (Poland) uses steam parameters of 27.5 MPa/560ºC/580ºC. The four 550 MWe coal-fired once-through SC CFBC boilers that are being installed in South Korea adopt steam parameters of 25.7 MPa/603ºC/603ºC. With the successful operation of the Lagiza SC CFBC power plant and more experience to be gained from the SC CFBC power plants being installed in Russia, China and South Korea, it is anticipated that future CFBC power plants will routinely use advanced steam parameters.

Other developments

Various forms of bottom ash cooling have been developed and work to improve the design of the ash cooler is continuing to minimise problems such as blockage. The waste heat from bottom ash is recovered, thereby raising the boiler efficiency. Over the past 20 years, improvements in refractory system designs, fuel and sorbent feed system designs, and ash extraction equipment design have been made that adequately address the initial problems encountered with these system components. As a result, the availability of CFBC systems have been improved and are considered to be generally equivalent to PC boilers. Furthermore, recent studies on fouling and corrosion caused by biomass and other difficult fuels led to modifications and optimisations in the design and operating parameters of CFBC boilers that cofire coal and biomass and/or waste derived fuels. A large number of multifuel-fired CFBC plants have been installed and operated successfully.

5.3 Oxy-fuel CFBC technology

Oxy-CFB boiler design challenges

The primary impacts of oxy-CFB combustion on the boiler concept and design are associated with the reduced combustion gas flow due to the removal of nitrogen present with air firing and the differences in the thermal and radiative properties of the gas comprised mostly of CO_2.

The main effect of increasing the O_2 content is a steep rise in the adiabatic combustion temperature, which will increase the need for heat transfer in the CFBC furnace and its share of the overall boiler heat duty. However, with higher O_2 concentrations, the volume of fluidising gases is reduced. As a result, the furnace cross sectional area and volume are decreased while the heat transferred in the furnace needs to be increased. This creates a challenge to manage the furnace temperature levels and to locate and develop designs for heat exchangers in the hot loop of oxy-CFB boiler. In addition, the impact of coal quality on oxy-CFB boiler design and operation needs to be established. Emissions of SO_2, NOx and other air pollutants under oxygen combustion conditions have been investigated in bench- and pilot- scale tests but more work is needed in order to determine the optimum operating conditions for different types of coal in terms of controlling air pollutant emissions in oxy-CFB combustion.

Developments in oxy-CFB technology

Fundamental studies into various aspects of oxy-fuel combustion have been carried out in facilities from laboratory to pilot scale primarily in research centres and universities around the world. Researchers and engineers from universities, manufacturers and utility companies are working together to develop and validate oxy-fuel combustion based CFBC power plants concepts. During 2001 to 2004, Alstom developed and validated oxy-CFB technology concepts through various technical and economic feasibility studies as well as several bench- and pilot-scale test campaigns. Currently, Foster Wheeler is the primary developer of oxy-CFB technology. FW has been developing an oxy-CFB combustion system called Flexi-Burn CFB, which is being used in the 30 MWth oxy-CFB boiler installed at the CIUDEN Carbon Capture Technology Development Centre (TDC) in Spain. Results from the CIUDEN Oxy-CFB demonstration project will be used to support and validate the scale-up of FW's Flexi-Burn CFB technology, as the basis for Endesa's Compostilla OxyCFB300 project. The project objectives are to validate the full chain of CCS technologies and to acquire the data for scaling-up oxy-CFB units. The CIUDEN CFB unit was commissioned and was first fired with coal in September 2011. The unit has been run successfully in both air and oxygen combustion mode.

Performance and costs

The power output of an oxy-CFB power generating unit will be lower compared with a corresponding air-firing CFB unit due to the additional auxiliary power consumption by the ASU and CPU units. In general, the efficiency penalty is about 10 percentage points in oxy-CFB operation compared to air firing. In terms of operation, bed agglomeration is not a major issue for a properly designed oxy-CFB boiler. SO_2 capture by lime/limestone in an oxy-CFB boiler occurs mostly via the direct sulphation route. No significant changes seem to occur in emission levels of SO_2 and NOx. CO_2 emission from air-fired CFB plant without carbon capture is 0.91 kg/kWh whilst the CO_2 released from the oxy-CFB plant with 90% of carbon capture is 0.077 kg/kWh. The emissions of mercury, VOC and other trace elements with oxy-firing and unburnt carbon-in-ash with O_2-firing are comparable to those with air-firing.

The total plant costs of an oxy-CFB plant are higher than those of the corresponding air-fired CFB plant due to the relatively costly and power consuming ASU and CPU systems.

Oxy-PC versus oxy-CFB

An oxy-CFB system has all the advantages of air CFBC technology such as fuel flexibility, good load-following capacity, the possibility to meet SOx and NOx emission requirements without additional flue gas cleaning equipment and a simple fuel feeding system. Compared with oxy-PC, oxy-CFB technology has additional advantages which include smaller unit size, easier transition between air- and O_2-firing mode, simple implementation relative to oxy-PC, reduced air in-leakage and lower excess O_2 which would result in lower operating costs. As with air-fired systems, ash produced by oxy-CFB boilers could be an area of concern.

Cost evaluations published in the literature are divided. A comparison between new oxy-CFB and oxy-PC power plant based on Alstom's 600 MWe (gross) SC CFB design with an oxygen concentration of 70% found that large oxy-CFBs could potentially be 10% cheaper than oxy-PC power plants. However, a cost and performance assessment of low-rank coal fired oxy-PC and oxy-CFB power plants with 90% CO_2 capture by NETL found that the estimated total plant costs (with contingencies) of oxy-CFB plants were higher than those of oxy-PC plants.

CFBC technology has advanced significantly in recent years making it competitive for coal-fired power generation. Oxy-CFB technology is developing rapidly and will evolve as the industry gains experience and incorporates new innovations. It is expected that CFBC technology will see increasing applications in the power generation industry in the near future.

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