CFB technology provides solutions for reducing CO_2 emissions

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Transaction Paper

Synopsis

The scheduled power cuts of early 2008 were a disturbing reminder that South Africa needs to expand its power-generating capacity. Low-grade and discard coals, of which South Africa has much, are a source of energy and amenable to combustion in circulating fluidized beds (CFBs). Foster Wheeler (FW) has a long record in developing this technology in boilers. The technology is flexible in burning a variety of fuels; low-grade, high-ash coals, good quality bituminous and anthracite coals, and biomass and waste fuels have all been used. CFB boilers are efficient, reliable and can be designed to meet tight emission standards.

In recent years once-through supercritical (OTSC) CFB technology has been developed. It enables the next stage in CFB development to proceed to a medium-scale (500 MWe) utility in such projects as Łagisza, which runs at a net efficiency of nearly 44%. Scaling the technology up to 800 MWe with a net efficiency of >45% is planned to be commercial during 2009.

CFB technology can reduce CO_2 emissions in the repowering of coal-fired and greenfield power plants. It does so through greater efficiencies and by co-combusting coal with biomass. FW has also developed CFB technology for the gasification of biomass, as, for example, in a pressurized gasifier to produce syngas, which can be used for the production of biodiesel, thereby reducing CO_2 emissions from vehicles.

Carbon capture and storage (CCS) can potentially cut CO_2 emissions in the generation of power from fossil fuels in the short term, provided that it gains public acceptance, that the required regulatory framework is created, and that emission-trading mechanisms or other incentives provide a solid return on the major investments required. Oxyfuel combustion is an option in CCS; Foster Wheeler is adapting its CFB combustion technology for oxy-fuel combustion to meet this challenge. It is developing Flexi-burn™, which enables a plant to be operated either with or without carbon capture.

This paper describes the status of CFB technology in terms of boiler efficiency and fuel flexibility. It highlights the advantages of CFB technology for oxyfuel combustion, presents a development plan for Flexi-burn™, and discusses a pressurized gasifier for biodiesel applications.

Introduction

Foster Wheeler is a global engineering and construction contractor and a supplier of power equipment. Among other products, the company offers state-of-the-art boilers for heat and electricity generation based on circulating fluidized bed (CFB) technology. Boilers are offered for a variety of fuels and mixes, including fossil-derived fuels (e.g. coal, waste coal, petcoke), peat, biomass-derived fuels (e.g. wood, agricultural residue, bio-sludge), and waste fuels (e.g. contaminated wood, REF, TDF).

During the past 30 years Foster Wheeler has booked nearly 350 CFB boilers, of which almost 240 are designed for coal and wastes from the coal mining industry with total thermal capacity of 47 000 MWth (Figure 1). All the boilers share the same circulating fluidization principle; however, depending on the quality of fuel, the boilers differ significantly in design and operation.

Power generation based on the combustion of solid fuels is expected to remain as mainstream technology for the foreseeable future. Fuel resources are abundant and widely distributed, which tends to provide price stability and security of supply. At modern power plants, the traditional pollutants are well under control. When considering either new plants or repowering of old plants, efficiency and environmental performance are key issues. High efficiency means lower fuel requirements, and lower levels of ash and emissions, including CO_2. In the near future the main market for CFBs in Europe will continue to be the replacement of existing old coal-fired units. Utilization of proven high efficiency CFB technology is an ideal solution both for repowering and for new plants. CFB technology has proven to have excellent fuel flexibility and also offer the option to co-combust of biofuels with different grades of coals, which can further reduce CO_2 emission[8].

CFB technology is now proven at utility-scale. Plant sizes up to 300 MWe are in operation today. The net efficiency of those

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 This paper was first published in the Industrial Fluidization South Africa, Conference (IFSA 2008), proceedings book, 19–20 Nov. 2008.

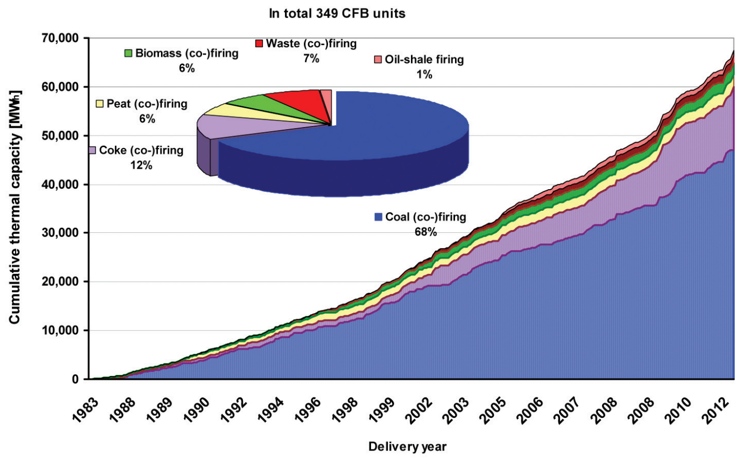


Figure 1—Foster Wheeler's CFB references (as at 02.09.2008)

conventional sub-critical designs is approximately 38-40%, depending on fuel and condenser conditions. During recent years, once-through supercritical (OTSC) CFB technology has been developed, enabling the next stage in CFB development to proceed medium-scale (<500 MWe) utility projects such as Lagisza, with net efficiencies near 45%. However, scaling up the technology further to utility scale (600-800 MWe) with net efficiency of 45–50% is needed to fulfil the future requirements of utility operators[8].

FW is continuously working on improving the efficiency and co-combustion capability of its CFB boilers. Efficiency increases and co-firing of coal with CO_2-neutral fuels provide a technically and economically feasible solution to the CO_2 issue in the short and medium term, while major emission cuts possibly required in the future call for more powerful solutions. Post-combustion capture of CO_2 from power station flue gases is considered technically feasible, but in combustion with air, the flue gas volumes are large and CO_2 very much diluted with N_2. Separation of CO_2 from such a stream is costly, and other options are being explored[8].

In oxyfuel combustion systems, the fuel is burned in a mixture of pure O_2 and recirculated flue gas, instead of air. The absence of air nitrogen produces a flue gas stream with a high concentration of CO_2, making its much easier to separate the CO_2. CFB technology appears to be ideally-suited for oxyfuel combustion, and FW is developing its CFB for oxy-combustion to provide the potential for nearly 100% reduction of CO_2[8]. The main focus at the moment is in a Flexi-burn™ concept, which enables the plant to be operated either with or without carbon capture, allowing more flexible operation and reduction of risks in plant operation.

High effeciency and fuel flexible CFB now in utility scale provides solution to reduce CO_2 emissions

Scale-up

Responding to an ever growing demand for power generation, CFB boiler technology has developed to meet utility-scale requirements (Figure 2). Today, the largest CFB units based on natural circulation are two 300 MWe CFB boilers at Jacksonville Energy Authority in Jacksonville, Florida, USA. These boilers burn either 100% coal or 100% petroleum coke or any combination of the two. The largest units in terms of physical dimensions are three 262 MWe CFB boilers at Turow power plant in Poland. The fuel for these boilers is lignite with moisture content of 45 wt %, which increases the flue gas flow considerably. The net efficiency of conventional sub-critical designs is approximately 38–40%, depending on fuel and condenser conditions.

During recent years, once-through supercritical (OTSC) CFB technology has been developed, enabling the next stage in CFB development to proceed to medium-scale (<500 MWe) commercial projects such as Lagisza, with net efficiencies near 45%. However, scaling up the technology further to utility size of 600–800 MWe with net efficiency of 45–50% is needed to fulfil the future requirements of utility operators.

Scaling-up of Foster Wheler's CFB boiler technology has been achieved through development of a second-generation design. This design features integration of the separator for circulating solids and the furnace (Figure 3a). A water/steam cooled separator replaced the hot cyclone with heavy refractory lining, which was distinctive for the first-generation design. This concept offers several advantages, such as:

- Less refractory in the system, thus reducing maintenance cost
- Shorter start-up time due to less temperature sensitivity in the refractory
- No expansion joints between the separator and the combustion chamber
- Smaller foot-print of the boiler, which can be very important in repowering schemes where the new boiler has to fit into an existing building or existing site.

The second-generation design was introduced in 1992, and in 1996 the design was enhanced with introduction of INTREX™—integrated heat exchanger located in the furnace (Figure 3b). INTREX™ extracts heat from the hot circulating material that is returned from the separator, or solids are taken directly from the lower part of the furnace. Continuous flow of dense solids enables high heat-rate coefficients within a small physical space, and prevents formation of deposits on tube surfaces. No mechanical devices are needed and all required controls are performed by air fluidization.

CFB technology provides solutions for reducing CO_2 emissions

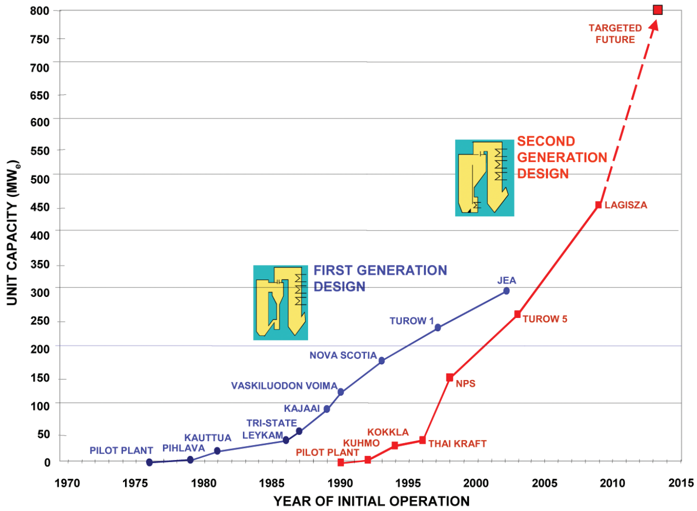
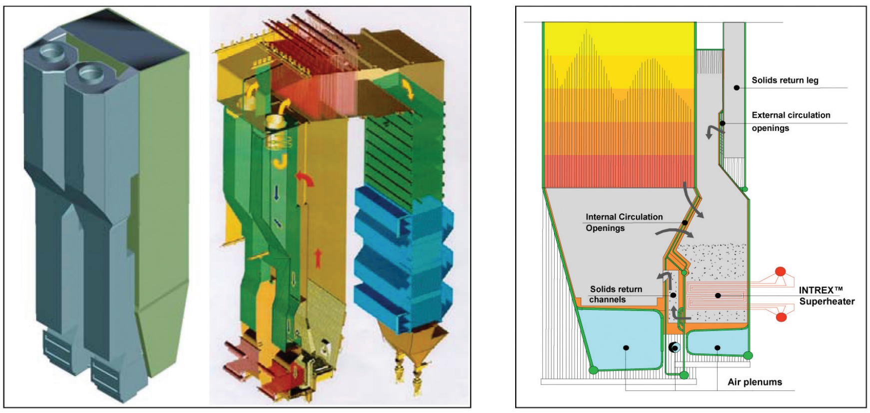


Figure 2—Scaling-up of Foster Wheeler's CFB boilers



(a) (b)

Figure 3—Features of second-generation Foster Wheeler's CFB boiler design: (a) water/steam cooled integrated separator (1992-), (b) INTREXTMsuperheater (1996–)

Superheaters and reheaters of INTREX™ type are particularly effective in designs for fuels that can cause corrosion on conventional heat surfaces, and for large-scale utility boilers.

Developing CFB technology to even larger sizes and higher plant efficiencies is an ongoing challenge. There is an increasing demand for boilers in the size range of 600 to 800 MWe, as existing power plants are aging and new replacement capacity has to be built. CFB technology is now emerging as an alternative plant of this size, thanks to the benefits it offers in terms of fuel flexibility and inherently low emissions. New, modern power plants need to have high efficiency for economic reasons and to minimize emissions, including CO_2. Plant net efficiency of approximately 45% (LHV) is expected. This calls for utilizing ultra supercritical steam parameters, together with an optimized power plant cycle and high boiler efficiency. Foster Wheeler develops design for 800 MWe CFB boiler with ultra-supercritical steam parameters. The scale-up of critical CFB components, such as the furnace, solids separators, and fluidized bed heat exchangers to 800 MWe is possible. The actual scaleup of the dimensions and size of plant components required is quite moderate, due to the modular approach adopted for the boiler design[7].

Reducing CO_2 emissions

Due to its economic advantage, abundance and shortage of alternatives, coal is expected to remain the dominant fuel for the foreseeable future, either for new power plants, or to replace older or inefficient units. A large number of coal-based plants will need to be built in Europe and worldwide in the next decade. However, CO_2 emissions from fossil-fired power generation are a major contributor to climate change. As a result, modern power plants are expected to comply with high efficiency and firm environmental performance. When considering either new plants or repowering of old units, utilization of proven high efficiency CFB technology is an ideal solution. High efficiency leads to lower fuel requirements, and lower levels of ash and emissions, including CO_2. In addition, CFB technology has proven excellent in fuel flexibility and co-firing of CO_2-neutral fuels with different grades of coals, which can further reduce CO_2 emission.

CFB technology provides solutions for reducing CO_2 emissions

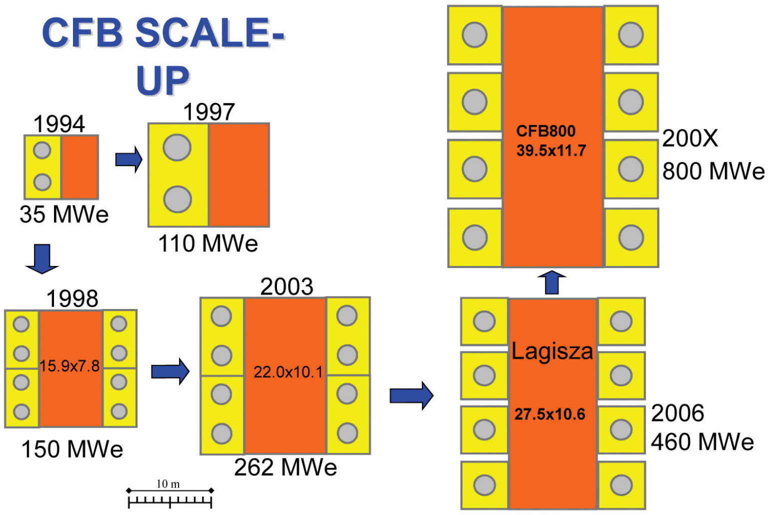


Figure 4—CFB Scale up, modular approach

Scaling-up CFB processes		Turow #5	Lagisza	CFB800
Main steam flow	kg/s	196	360	568
Main steam pressure	MPa	17	27.5	30.9
Main steam temperature	°C	568	560	600
Reheat steam flow	kg/s	181	307	489
Reheat steam pressure	MPa	3.9	5.5	4.5
Reheat steam temperature	°C	568	580	620
Design capacity	MWe	262	460	760
Net electrical efficiency	-	39	44	>45
Boiler type	-	drum	OTSC	OTSC

Figure 5—Scale up of steam parameters

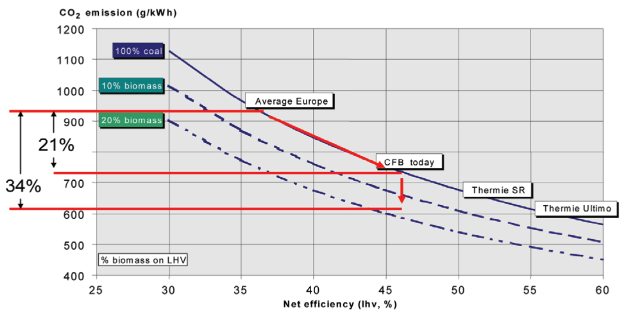


Figure 6—Impact of efficiency improvement and biomass co-firing on CO_2 reduction

Reduction of greenhouse gas emissions has become a major challenge for the energy producers and technology suppliers. Currently, the main approach to reducing emissions is to increase efficiency. When combined with other solutions, efficiency improvement has a direct impact on the consumption of natural resources, the generation of waste matter and the economics of production.

Co-firing of solid fossil fuels with CO_2-neutral fuels in highly fuel-flexible CFB boilers provides a technically and economically feasible solution for CO_2 reduction up to certain degree, both in repowering and greenfield applications[3].

Advantages of CFB technology with emphasis on fuel flexibility

Circulating fluidized bed (CFB) process provides an ideal burning environment for a wide variety of fuels. The advantages of CFB technology can be summarized as follows:

- Fuel flexibility and multi-fuel firing
- Low SO_2 emissions due to efficient sulfur capture with limestone in the furnace
- Low NO_x emission due to low combustion temperature and air-staging
- Low CO and C_xH_y due to turbulent conditions and good mixing,
- Secondary flue gas clean-up systems typically not needed
- Stable operating conditions and good turn-down ratio
- Support firing is not needed except during start-up periods
- Increased capacity possible within the same footprint as old boilers
- No need for fuel preparation (e.g. pulverizing).

One of the important advantages of CFB technology is the possibility of burning a diverse range of fuels alternately and/or simultaneously. Fuel flexibility includes both a wide range of heating values and the possibility of burning fuels with very different physical and chemical properties. The types of fuels used in CFB boilers include coal of various degrees of carbonification, waste coal, petroleum coke, peat, wood-derived fuels, agricultural and agro-industrial wastes, sludge, refuse derived fuels, tires, etc. (see Figure 7). Figure 8 compares chemical properties of a few selected fuels used in commercial boilers.

CFB boilers can effectively deal with wide variations in coal quality, which can exist even within coals from a single mine. In an attempt to minimize the operational costs, utilities seek possibilities to utilize cheaper, lower-grade coals with high moisture, ash and sulphur content (see also Figure 8). Low-grade coals that have already been used in power production, especially in Poland, which uses local lignite coals or lower-rank bituminous coals, which do not have an export market due to low quality. Utilization of these coals in old

Coal
- Anthracite
- Bituminous
- Sub-bituminous
- Lignite

Wood residue
- Bark
- Chips
- Wood dust
- Forest residue

Recycled Wood

Tire Derived Fuel

Solid Recovered Fuel

Waste coal
- Bituminous gob
- Anthracite culm
- Coal slurry

Agricultural waste
- Straw
- Olive waste

Waste paper

Gas
Natural
“Off” gases

Petroleum coke
- Delayed
- Fluid

Sludge
- Paper mill
- De-inking
- Municipal

Oil

Oil shale

Peat

Figure 7—Type of fuels (co-) fired in Foster Wheeler’s CFB boilers

pulverized coal and stoker fired boilers—which usually were not equipped with either desulphurization or proper dust removal installations—have caused many environmental problems in the form of gaseous and dust emissions. However, low-grade coals have been used in environmentally sound way in a number of high efficiency CFB boilers; examples of two power stations, Turów and Jaworzno, utilizing local low-grade coals will be given in the following section.

The possibility of using coal washind discards in CFB boilers has proved particularly valuable in Poland; for example, in power station Jaworzno. Modern CFB technology provides an efficient and profitable way to produce power from these wastes, which would otherwise need to be disposed of in a landfill, while also providing some profit from the waste coal rather than paying fees for its disposal.

At present, most CFB installations are designed for multi-fuel firing capability, i.e. for more than one solid fuel[1]. Coal and peat are common fuels in multi-fuel CFB installations together with wood or wood-based fuel[8].

Utilization 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. However, the physical and chemical characteristics of the diverse spectrum of biomass fuels vary widely[12]. Utilization of biomass fuels in CFB boilers may cause operational problems, such as agglomeration, deposit formation, and corrosion[2,4]. 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 or peat that can capture problematic elements from biomass/wastes. Coal co-combustion is applied for example in NPS utility in Thailand, to fire high shares of local biomass rice husk and eucalyptus bark.

The following section will briefly present examples of utilization of CFB technology in repowering, and in multi-fuel combustion option. Details of discussed projects can be found in publications by Hotta *et al.*, 2008[5]; Jäntti *et al.*, 2006[8]; Psik *et al.*, 2005[10]; Hotta, Venäläinen, 2006[7]; Hotta *et al.*, 2005[6]; Venäläinen, Psik, 2004[13]; Navarrete Fernández, 2003[9]; Pyykkönen, Hotta, 2000[11].

Repowering with high efficiency CFB

Over 60 % of existing coal-fired power plants throughout Europe are more than 20 years old, and many with modest efficiency[8]. Consequently, this will result in a substantial need for new thermal power plants in the near future.

Depending on local, regional or country environmental performance standards, CFBs can often meet emission limits without any secondary flue gas cleaning systems, and plant owners do not need to be concerned about the costs or space requirements of flue gas desulphurization or selective catalytic reduction units. A CFB boiler can typically fit into an old boiler house. However, it is seldom possible to use the old steel structures or foundations, as the boiler loads differ from the original boiler. What is important, however, is that boiler output and efficiency can be increased. Foster Wheeler has wide experience in repowering projects in the scale of 200–300 MWe. Today's CFB technology can reach 45% efficiency when utilizing the supercritical steam parameters[8].

Turów power station S. A., Bogatynia, Poland

One of the most remarkable repowering projects using fluidized bed technology is the Turów power station in the Silezsia region of southern Poland. This station, originally comprising 10 units, each of 200 MWe in capacity, has undergone an extensive repowering process: three of the units were rehabilitated with back end emission equipment, six units were replaced with CFB boilers, and one unit is decommissioned. The space available for the new units was very limited; however, CFB boilers could fit into the old boiler house sections.

CFB technology was considered ideally suited for burning Polish lignite coal, for which design values of LHV, moisture content, ash content and sulphur content varied in the ranges 7.1–10.2 MJ/kg, 40–48 wt %, 6.5–31.5 wt % and 0.4–0.8 wt %, respectively. For the fuel properties see also Figure 8.

The Turów power station with six CFB units is currently the largest in the world based on fluidized-bed technology. The first three units are of conventional CFB design, and were delivered in 1998—Units 1 and 2 and, in 2000, Unit 3. Second-generation design was selected for the last three

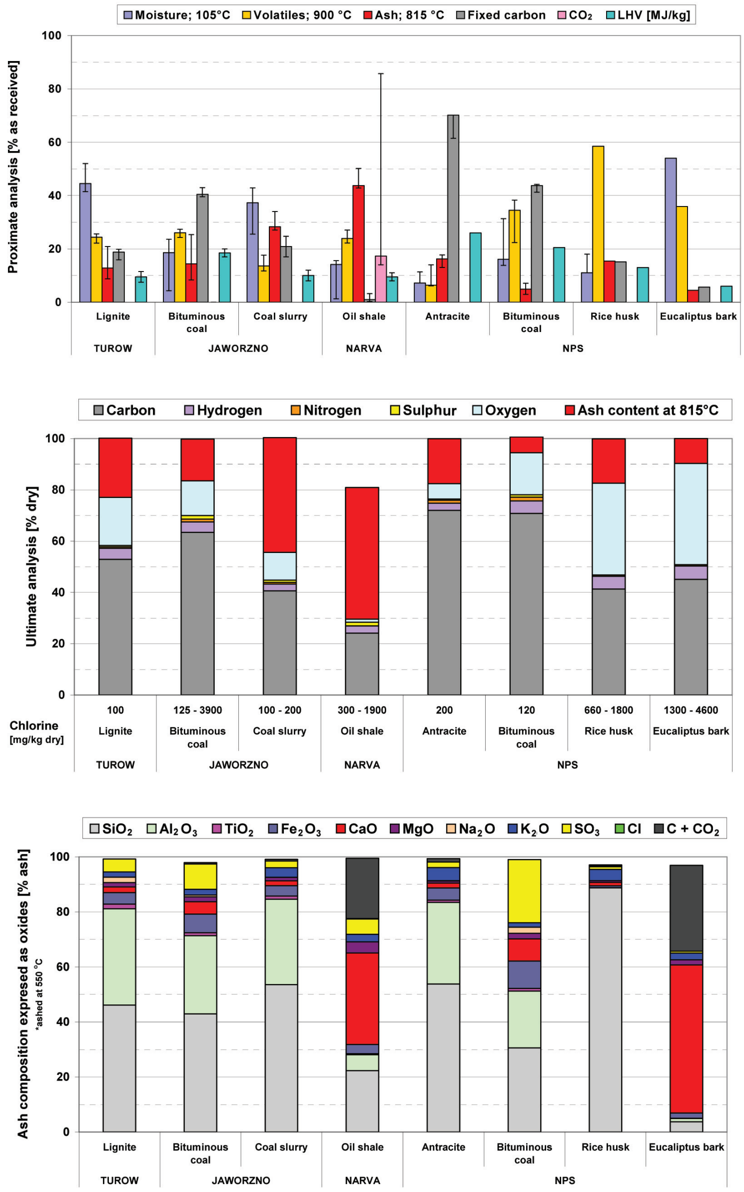


Figure 8—Fuel properties (data from Foster Wheeler's fuel database)

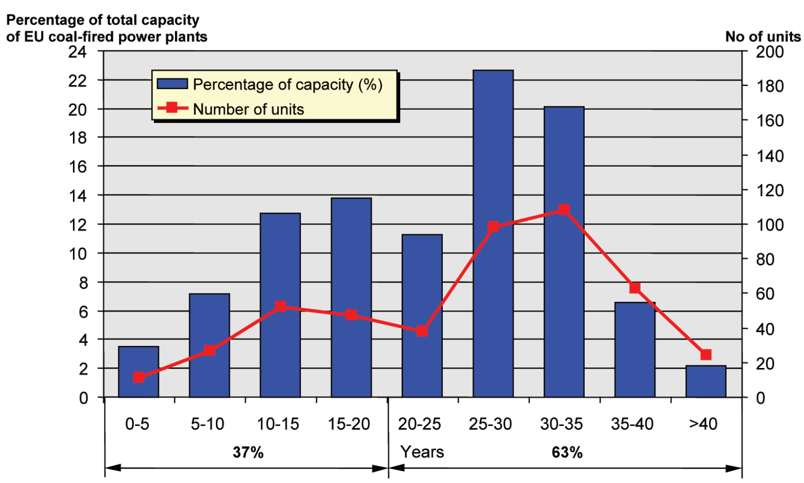


Figure 9—Age structure of power plants in European countries (taken from Jäntti, 2006)

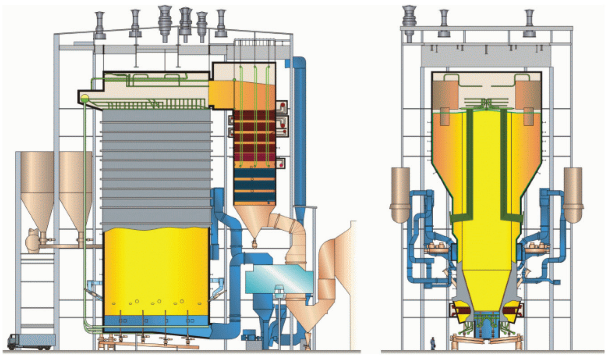


Figure 10—Cross-section of Turow Power Station S.A. units 4–6

units, which were delivered in 2002—Unit 5 and, in 2004 Units 4 and 6. Implementing the second-generation design increased the capacity to 262 MWe instead of 235 MWe, within the footprint of the old pulverized coal 200 MWe units. Better steam values and better overall performance also led to better overall efficiency: 40.4% compared to 31.2% of original boilers[8]. The comparison of main boiler data is shown in Table I. The cross-section of Turow power station S.A. units 4–6 is shown in Figure 10.

Guaranteed emissions are shown in Table I. Good emission control in the CFB boiler is achieved by low combustion temperature and even temperature profile through the height of the furnace, a staged combustion, good residence times and mixing conditions.

The Turów power station is now in successful operation, and meeting all guarantees. It is noteworthy that there has been a considerable emissions reduction compared to the original situation: NO_X has been reduced by 19%, SO_2 by 92%, dust by 91% and CO_2 by 24%.

Elektrownia Jaworzno III S.A., Jaworzno, Poland

In the Jaworzno project three old pulverized coal fired boilers were replaced with two 70 MWe CFB boilers firing local high-ash and high-moisture bituminous coal. In addition, these boilers can fire up to 50% of energy input, coal slurry that is delivered from the adjacent coal-mines (Figure 11). Fuel properties are summarized in Figure 8.

The boilers utilize the second-generation of the Foster Wheeler CFB design with compact separators and INTREXTM superheaters (Figure 12). Steam and feed-water data of one boiler at nominal capacity are:

- Total heat output MWth 180
- Steam flow kg/s 72.2
- Steam pressure bar 137
- Steam temperature °C 540
- Feedwater temperature 220 °C

The boilers have been in commercial operation since November 1999.

AS Narva Elektrijaamad, Narva, Estonia

Estonia's electricity generation is more than 90% based on combustion of oil-shale. AS Narva Elektrijaamad owns and operates the two largest oil-shale-burning power plants in Estonia (and worldwide), Eesti and Balti, located near the town of Narva. A combined installed capacity of two power plants is 2 705 MW of electricity and 589 MW of district heating. Plants, originally build with pulverized fuel (PF) technology, were commissioned during the 1959–1973. Due to their age and poor economic and environmental performance related to PF firing of oil shale, the utility decided to repower two 200 MWe units with fluidized-bed technology. After preliminary investigations and pilot-scale combustion tests, CFB technology was found to be the most

Table 1

Main boiler data for Turow Power Station S.A. units 1–6

		Boilers	
		No. 1–3	No. 4–6
Capacity	MWt	528.9	557
Main steam flow	kg/s	185.4	195.5
Main steam pressure	bar	131	169
Main steam temperature	°C	540	565
Reheated steam pressure	bar	24	39
Reheated steam temperature	°C	540	585
Guaranteed emissions, 6% O_2 content, dry flue gas			
NO_x	mg/Nm^3	371	
SO_x	mg/Nm^3	347	
CO	mg/Nm^3	150	
Dust	mg/Nm^3	50	

Figure 11—Coal slurry

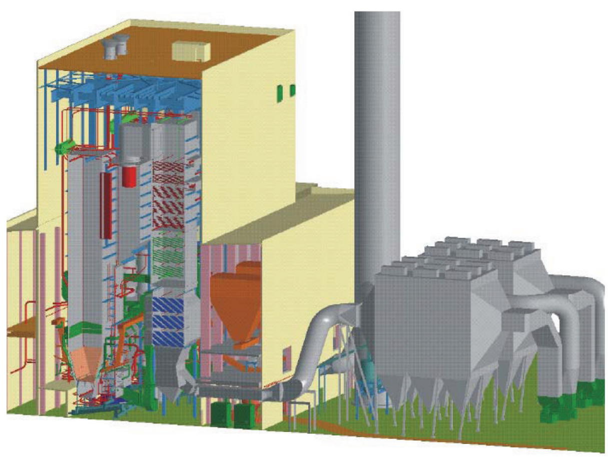


Figure 12—Cross-section of Elektrownia Jaworzno III S.A. CFB unit

suitable for oil shale firing in terms of process behaviour and gaseous emissions. The engineering, procurement and construction (EPC) contract for the design and supply of four new 100 MWe CFB boilers was signed between AS Narva Elektrijaamad and Foster Wheeler Energia Oy in May 2001. The project also included the modernization and upgrading of two existing 200 MWe steam turbine-generators to 215 MWe. The first of the new blocks, Eesti block 8, started commercial operation in February 2004 and was followed by Balti block 11 later during the same year. The units are designed to produce 90 kg/s of superheated steam at 13.1 MPa pressure and 540 °C temperature, and reheat steam at 2.7 MPa pressure. The load range 40–100 % of MCR.

Estonian oil shale is a very difficult-to-burn fuel due to its unique properties (see Figure 8). High alkali and chlorine content in oil-shale ash has caused significant corrosion and fouling problems in PF units, resulting in decreased availability. Gaseous emissions, especially SO_2 and particulate emission, have been high. In CFB combustion the SO_2 emission is considerably reduced due the inherent limestone content of oil-shale ash, which favors sulphur capture in CFB conditions. SO_2 and NO_x emissions have been reduced by 90% and 30%, respectively, while particulate emission has decreased significantly compared to the old PF units with less efficient electrostatic precipitators (ESP). Improved efficiency and decreased carbonate decomposition in CFB has decreased the CO_2 emission per produced power unit by nearly 24%.

In the CFB boilers, fouling and corrosion problems in the convective superheaters have been prevented by careful choice of steam temperature for each superheating stage and by using effective heat surface cleaning methods. INTREX™ superheaters are used as the last super-/reheating stage and refractorylined separators as second superheating stage, allowing lower steam temperature to be used in convective super-/reheater sections where the risk of high-temperature corrosion is highest. The new CFB boilers use pneumatic fuel feeding with many feeding points, resulting in good fuel mixing and providing favourable conditions for sulphur binding in the lower furnace (Figure 13).

The careful CFB boiler design has resolved the problems related to oil shale combustion: during the first year of commercial operation no signs of significant fouling or corrosion of heat exchangers has occurred in the new boilers at the Narva Power Plants. Improved availability, lower maintenance costs and higher efficiency of the new units have significantly improved the unit's economics. According to the performance tests, the net efficiency of the CFB units is 38–39%, whereas in the PF units it is in the range of 29–30%. A big part of the efficiency improvement is deriving from the lower carbonate deposition and higher sulphation rate in CFB combustion, the effect of which is about 0.4 MJ/kg or 5% comparing with PF[5].

Eesti and Balti power plants were granted a transition period concerning the EU Large Combustion Plant Directive emission limits until the end of 2015, after which the old PF blocks must be out of service. Due to positive experiences from two first units repowered with CFB technology, Narva Power Plants is planning to proceed by repowering two to five additional 200 MWe units with CFB technology, the best available technology for oil shale firing.

Poludniowy Koncern Energetycny (PKE), Lagisza, Poland

CFB is not only suitable for hard-to-burn fuels, but the technology is also ideally suited for quality bituminous coal. Through a continuous scale-up and development process, CFB technology has now reached medium utility scale with once-through supercritical boiler technology.

Utilizing Siemens' BENSON low mass-flux vertical tubing technology offers some clear advantages for CFB technology, including a lower pressure drop over the furnace tubing, resulting in less power needed for feed water pumps and lower auxiliary power consumption. The combustion temperature in a CFB is homogenous both vertically and horizontally, which means that the heat flux is relatively uniform, and the risk of overheating is not present as it is in conventional technology with a heat flux that can be up to three times higher locally.

The first company to benefit from OTU CFB technology with supercritical steam parameters will be the Polish utility,

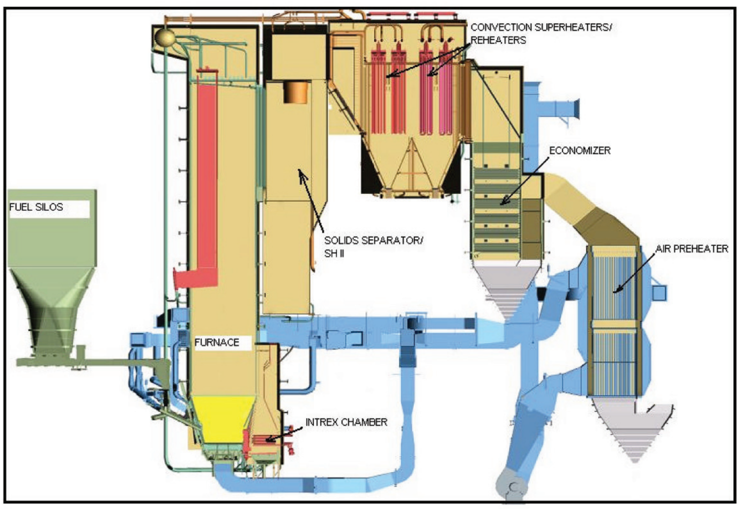


Figure 13—The basic design of the CFB boilers at the AS Narva Eletkrijaamad power stations

Poludniowy Koncern Energetyczny S.A. (PKE). The new 460 MWe (gross) unit will replace old power blocks of Lagisza Power Plant. The existing blocks were erected in the 1960s and consist of seven units (110–125 MWe each). Two of them will be shut down after the new 460 MWe unit is commissioned. The new boiler will be built adjacent to the old boilers and many of existing plant systems such as coal handling and water treatment will be renovated and utilized for the new CFB unit.

The main fuel for the boiler is bituminous coal. The source of fuel consists of 10 local coal mines with wide range of coal parameters, proving once more the fuel flexibility of the CFB technology. Table II summarizes the parameters of design fuel and overall fuel range. Boiler design is optimized with a possibility for combustion of additional fuels. The main additional fuel is coal slurry that is available in large amounts in local coal mines. Due to CFB technology characteristics, wet coal slurry can be combusted with 30% share of fuel heat input. Coal washing discard can also be burned in form of dry coal slurry granulates with a share up to 50% of heat input. The boiler is designed also to utilize biomass fuels up to 10% of fuel input. The biomass feeding equipment is included in the delivery as an option.

The Lagisza CFB boiler is dimensioned according to data given in Table III. The general boiler layout was based on the conventional in-line arrangement already applied for Units 4–6 of the Turów power plant. Figure 14 shows schematics of the boiler. Detailed description of the once-through boiler design and related aspects can be found in[13].

The emission requirements for the Lagisza boiler are according to the European Union directive for Large Combustion Plants, and considerable emission reduction is expected compared to the existing PF unit. The emissions of sulphur dioxide are controlled with limestone feeding into the furnace. With the design coal a sulphur reduction of 94% is required, and that shall be achieved in the CFB with a calcium to sulphur molar ratio of 2.0–2.4. The nitrogen oxide emissions are controlled with low combustion temperature and staged combustion. There are also provisions made for a simple ammonia injection system (SNCR). However, this not required on design coals. Compared to original plants, NO_x emissions are expected to be reduced by 71%, and CO_2 by 28%. Particulate emissions are controlled by electrostatic precipitator. The plant efficiency is expected to be improved from 34.7% to nearly 44%.

Table II

Fuel properties for the Lagisza project

		Coal range	Coal slurry range (max 30% input)
Lower heat value	MJ/kg	18–23	7–17
Moisture content	%	6–23	27–45
Total ash content	%	10–25	28–65
Sulphur content	%	0.6–1.4	0.6–1.6

Table III

Boiler data for the Lagisza 460 MWe CFB boiler

Maximum continuous flow	kg/s	359.8
Minimum continuous flow	kg/s	143.9
HP steam pressure at turbine inlet	MPa	27.50
HP steam temperature at turbine inlet	°C	560
Cold reheated steam flow	kg/s	306.9
Cold reheated steam pressure	MPa	5.46
Cold reheated steam temperature	°C	314.3
RH steam temperature at IP turbine inlet	°C	580
Feed water temperature	°C	289.7

Multi-fuel combustion in CFB boilers

Foster Wheeler is continuously working on improving the co-combustion capability of its CFB boilers. From a technical standpoint, co-firing of biomass and waste appears best in large coal-fired units, where all available biomass and waste can amount to only a minor share of the thermal input. In return, the coal-fired unit benefits from more economical fuels and better CO_2 performance. In addition, co-combustion of biomass and waste fuels is an effective method to counteract agglomeration, fouling and corrosion, difficulties, which often arise during combustion of these types of fuel. In this case, compounds contained in coal capture the problematic elements from biomass and waste, with no additional losses or costs[2].

National Power Supply Co., Ltd. (NPS) Power Plant, Tha Toom, Thailand

The National Power Supply Co., Ltd. (NPS) Power Plant, located in Tha Toom village of Prachinburi province in Thailand, started commercial operation in February 1999 (Figure 15). The power plant is equipped with two identical units of 150 MWe or 370 MWth. Each unit is designed to produce 134 kg/s of superheated steam at 162 bar(a) pressure and 542 °C temperature, and 122 kg/s of reheat steam at 542 °C temperature and pressure of 16 to 38 bar(a) depending on boiler load.

The NPS Power Plant is feeding 60% of its power output to the Electricity Generating Authority of Thailand (EGAT) under Thailand's small power producer (SPP) programme. The process steam and the remainder of the power are sold to

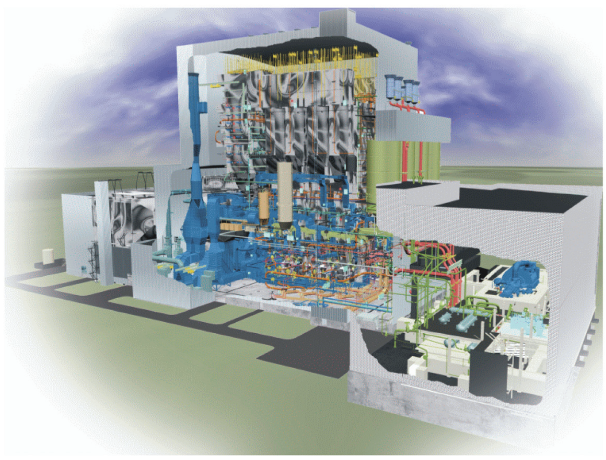


Figure 14—The 460 MWe once-through CFB at PKE, Lagisza

CFB technology provides solutions for reducing CO_2 emissions

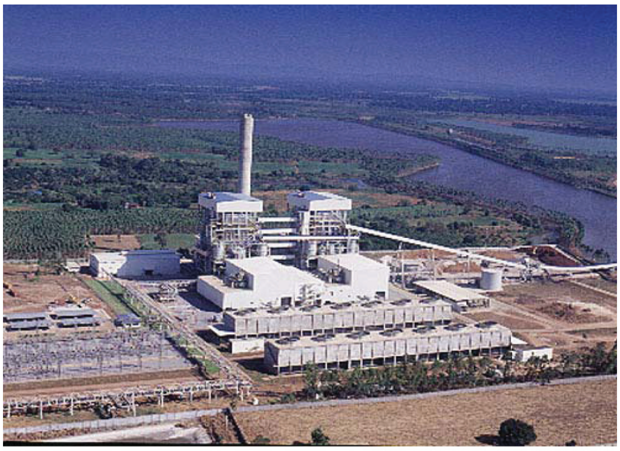


Figure 15—Two CFBs at the NPS power plant in Thailand

local customers of Industrial Park 304 and to the nearby Advance Agro pulp and paper mill.

The main fuels used in both boilers are anthracite and/or bituminous coal, and additionally, the boilers are designed to co-fire local biomass up to $50\%_{en}$: rice husk and eucalyptus bark. Rice husk is purchased from the local suppliers while eucalyptus bark is a waste product from the nearby Advance Agro pulp and paper mill.

As can be seen from Figure 8, chemical properties of the biomass fuels differ significantly between each other, and from those of coals. Rice husk is a very special biomass fuel with ash content of 15–20 wt% in dry solids, which is higher when compared to other biomass fuels. Rice husk ash contains over 90% SiO_2 in most cases, making it very different from the straws of other cereals and even the rice straw ash. It does not cause fouling or slagging, but has slightly erosive effect due to a large particle size and sharp edged SiO_2 particles in ash. The erosivity of rice husk is high enough to 'sand blast' the boiler to some extent when co-fired with, for example, eucalyptus bark that has ash with fouling propensity[4].

Eucalyptus bark is another exceptional biomass that can contain very high contents of chlorine. Concentrations up to 0.98 w % have been analyzed, although normally the values are 0.2–0.3 w % in dry solids[4]. Combined with ash composed mainly of calcium and potassium compounds, such high chlorine level is known to increase boiler fouling and superheater corrosion.

Fired in high efficiency boilers with high steam temperatures and pressures, the negative properties of such biomass fuels and their ashes are amplified. Nevertheless, thanks to proper understanding of interactions among ashes of co-fired fuels and reactions of flue gas components with the ash components, both rice husk and eucalyptus bark have been efficiently utilized in two NPS boilers that feature the second-generation CFB design with INTREX™ superheaters. The boilers have been in successful operation for nearly ten years, with good availability.

CCS as the future near zero CO_2-emission solution

When bigger emission cuts are required, CCS offers potential for near zero emission power production from fossil fuels, though at the expense of efficiency and costs. FW is developing currently oxy fuel CFB-technology, which is seen to be the most feasible alternative for CCS at the moment.

Figure 16 shows a simplified process flow scheme of an oxycombustion power plant, which consists of an air separation unit (ASU), a power plant with O_2-blown combustion, and a CO_2 treatment unit. Oxygen is mixed with recirculated flue gases, which creates a mixture of primarily O_2 and CO_2 (and H_2O) used as oxidant in combustion instead of air. The absence of air nitrogen produces a flue gas stream with a high concentration of CO_2, making it much easier to separate the CO_2. CFB technology appears to be ideally suited for oxyfuel combustion, and as a longer term activity, FW is developing its CFB for oxycombustion to provide the potential for nearly 100% reduction of CO_2[3].

Oxy-CFB technology, the Flexi-burn™ CFB, is being developed for existing boilers as a retrofit solution, for new 'capture ready' boilers to be modified for CCS in the future, and for integrated greenfield power plants with CCS from the beginning. Designing an oxyfuel power plant calls for case-specific optimization of the performance and economics. Normal boiler designs with reasonable modifications can be applied, if the mixing ratio of oxygen and recycled flue gas ratio is chosen so that the adiabatic combustion temperature is close to that of air firing. Such a plant could even be operated either with or without carbon capture and thus with lower or higher output, for instance depending on the price of CO_2 allowances and electricity[3].

The 460 MWe once-through supercritical coal fired CFB

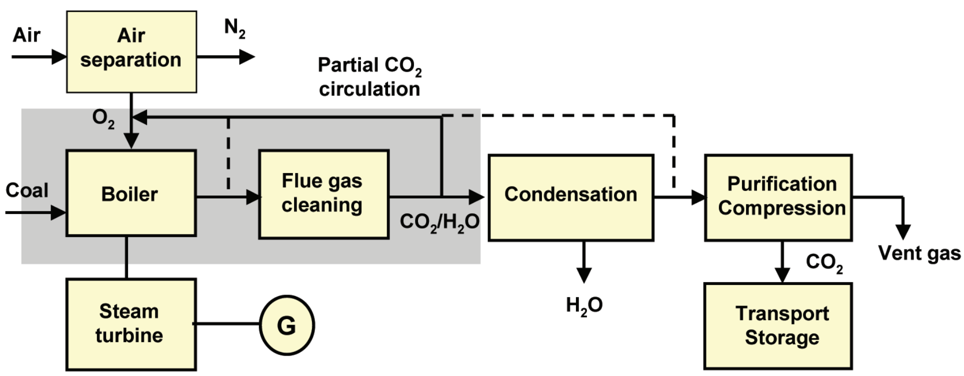


Figure 16—Schematic of an oxycombustion power plant

boiler plant being designed and constructed by FW for the Polish utility PKE at Lagisza power plant has been used as a starting point and reference in an study that considers plant optimization items and aims to generate knowledge about boiler conversions for oxyfiring and design of new 'capture ready' boiler plants. High-O_2 designs provide potential for cost savings and higher efficiency but require an entirely new boiler concept, and will be a subject of future studies[3].

Flexi-Burn™—CFB boiler conversion to oxyfiring

Foster Wheeler is currently developing a Flexi-burn™ concept, which enables the plant to be operated either with or without carbon capture. The net output of the plant would be lower or higher, respectively. Start-up is likely to take place through air firing followed by gradual shift to oxyfuel combustion and carbon capture. This concept would primarily reduce risks due to for instance failures in ASU, CPU or transport and storage equipment, by allowing the boiler to be operated in air-firing mode without additional shutdowns. In principle, it also allows more flexible operation depending on the price of CO_2 allowances and electricity and power requirements.

Along with the development of CFB combustion technology from small industrial scale to large supercritical utility boilers, FW has developed in-house boiler design tools enabling rigorous design and performance prediction of CFB combustors for a variety of fuels and operating conditions. FW design tools are being modified to include the specific features related to oxyfuel combustion. Development and validation of all the required submodels for oxycombustion conditions requires significant amounts of experimental data, also from large units that do not exist yet. Nevertheless, the models and the commercial Aspen Plus® software are already being used for creating oxy-CFB boiler designs[3].

FW studied options of Lagisza boiler conversion to oxy-fuel combustion. The FW CFB boiler thermal design and calculation programme is used to study conversion of the Lagisza CFB boiler for oxyfuel combustion. The basic assumptions are as follows[3].

- The furnace remains unchanged, but internal heat surfaces may be modified
- The total gas mass flow rate and excess O_2 level are similar to air firing.
- The rotary air preheater is utilized, if possible, for reheating of recirculation flue gas, the flow rate of which is slightly lower than that of air (in the reference case).
- The oxygen purity is 95 v %, and the rest is assumed to be nitrogen. The effect of O_2 purity is small on boiler design but significant in the overall process optimization
- Air ingress into the boiler is not taken into account. It reduces the performance, but the allowable leak rates depend on the selected purification process and required CO_2 purity. The issue can be abated by sealing points of leakage, replacing auxiliary air streams into the boiler with dry CO_2, or designing the boiler for slight overpressure
- Flue gas cleaning is similar to the air-fired reference case.

Figure 17 shows the process connections used in the study in a simplified form. The following cases were evaluated[3]:

- Air-firing as the reference case
- Case 1: Oxycombustion with reduced in-furnace heat surfaces
- Case 2: Oxycombustion with original in-furnace heat surfaces
- Case 3: As Case 2 but with reduced flue gas recycle rate (i.e. higher oxidant O_2 concentration and lower velocities, but similar steam capacity).

The combustor temperature was varied in different cases, partly due to expected differences in the sulphur capture mechanisms compared with air firing. In the studied oxyfiring cases the flue gas CO_2 content is around 60 %-vol.

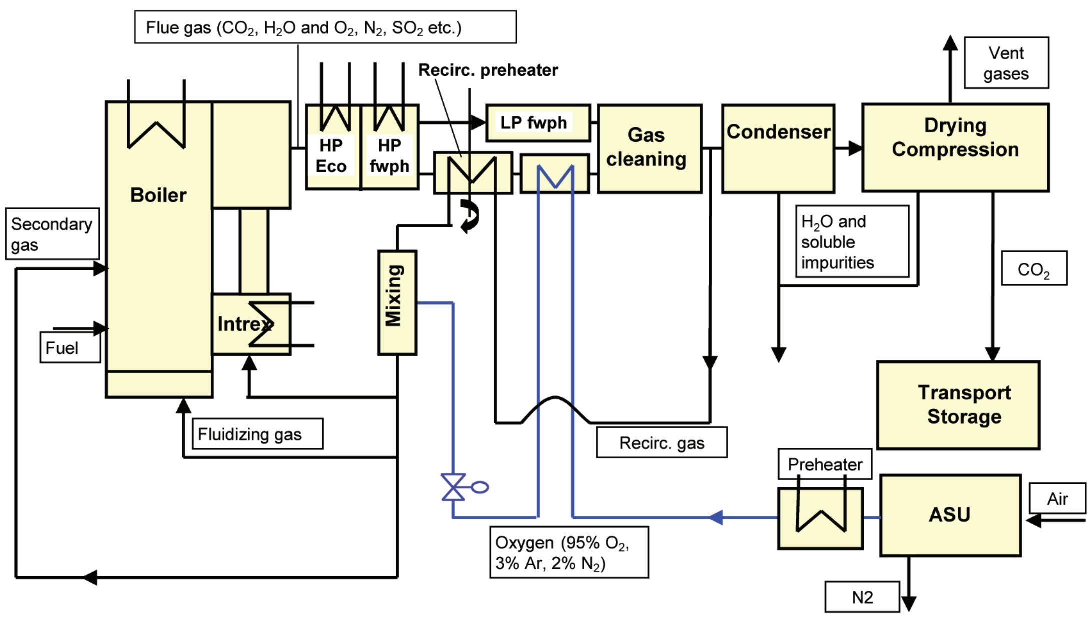


Figure 17—Process flow scheme

(in wet gas, with wet flue gas recycle), which corresponds to a temperature of 860–870 °C on the theoretical $CaCO_3$-CaO equilibrium curve. Therefore, sulphur capture could occur through the calcination-sulphation route as in normal fluidized bed combustion, or through direct sulphation as in pressurized combustion. Based on laboratory-scale studies and experiences of pressurized combustion, it is known that direct sulphation can be very efficient and lead into better limestone utilization. Moreover, avoiding calcination would also reduce the related energy losses and deposit formation due to recarbonation. However, so far there are not adequate experiences of real oxycombustion conditions with flue gas recycle to be able to fix the optimal process temperature[3].

Results of the boiler calculations

Table IV shows some main process values of the air-fired reference and the studied oxyfuel cases at 100% load. The balance envelope has been set so that the flue gas heat recovery system cooling the gas below 100 °C even in the reference case is not included[3].

The O_2 content of the oxidant results from the initial assumptions, and in Cases 1 and 2 it is only slightly higher than in air firing. In Case 3 the smaller recirculation gas causes a higher O_2 content, and also the adiabatic combustion temperature would be higher than in air firing, while in the other cases it would be lower. Vertical temperature profiles are rather flat in all the cases. Preheating of oxygen was limited to a maximum of 200 °C, and therefore the oxidant is not as hot as preheated air. Higher flue gas density and constant mass flow rate cause the reduction of fluidization velocity[3].

As indicated by the flue gas flow rates, only 29% of the total flue gas in the boiler is 'fresh' combustion gas and the majority is recirculated gas. Reduced recirculation gas (Case 3, 36% combustion gas) results in a slightly steeper temperature profile but appears feasible. The same approach cannot be applied at low loads due to minimum velocity requirements[3].

The CO_2 content of dry flue gas rises to about 90%, and the rest consists mainly of N_2 (+Ar) and O_2 coming from the feed oxygen. Such a high share of gaseous impurities would in practice require further CO_2 purification. O_2 purity is a process optimization issue, while defining the excess O_2 level in oxycombustion calls for more experimental and modeling work. Low flue gas flow rates result in improved boiler efficiency in spite of higher flue gas exit temperatures. In downstream components the flue gas would be cooled and condensed, and appropriate heat sinks would have to be found in the process[3].

Pressurized gasifier for biodiesel syngas production

Foster Wheeler has supplied numerous biomass gasifiers, both atmospheric and pressurized applications. Interest in gasification has increased lately due to political decisions to substitute conventional fuels by alternative biofuels in the road transport sector. Total EU liquid biofuel demand is assumed to be 18 Mtoe/a in 2010 while production in 2004 was around 2 Mtoe/a.

By 2020 the estimate for required production of second generation Fisher-Tropsch (FT) biofuels is about 10% of all petrol and diesel for transport purposes, which means about 30 Mtoe/a. Concentrating on the production of FT liquids seems to be the most promising option in the short and medium term. Synthetic diesel, which is produced via Fisher-Tropsch synthesis, can be used directly in diesel engines either on its own or mixed with conventional diesel fuel. No new distribution networks are needed.

Foster Wheeler, together with Neste Oil and other Finnish-based industrial partners has participated in Finnish Ultra Clean Gas (UCG) development programme led by Technical Research Centre of Finland, which was realized in 2004–2007. The programme was targeted to develop an advanced process for producing multipurpose synthesis gas from solid biofuels. The experimental work was focused on an optimized fluidized-bed gasification process and development of the gas conditioning and cleaning process to meet the requirements for the FT liquids, synthetic natural gas (SNG) and other possible synthesis gas utilization technologies, e.g. hydrogen and methanol production. The Finnish concept for biodiesel production is presented in Figure 18.

The developed process is based on pressurized oxygen-steam blown fluidized-bed gasification followed by novel catalytic gas reforming technology. The new gasification process is designed for a wide range of feed stocks including woody biofuels, peat, straw and other agro biomasses, as well as various waste-derived fuels. The novel gas cleaning technology eliminates the tar problem, maximizes the syngas yield and makes it possible to adjust the H_2/CO ratio of the syngas. The synthesis gas can be raw material for various end products: Fisher-Tropsch liquids, methanol, synthetic natural gas (SNG) and hydrogen.

Table IV

Process Values

	Reference	Case 1	Case 2	Case 3
Oxidant	Air	O_2+fg	O_2+fg	O_2+fg
O_2 content of oxidant (%, wet)	20.6	23.9	23.9	29.6
Steam capacity (MW)	965	1022	1018	1003
Fuel input, LHV (MW)	1020	1069	1068	1044
Furnace exit temperature (°C)	864	900	867	899
Flue gas mass flow, total (kg/s)	457	461	459	364
Flue gas to stack (kg/s)	457	132	131	130
Flue gas oxygen, dry (%)	3.6	3.7	3.7	3.7
Flue gas CO_2, dry (%)	14.9	90.3	90.3	90.3
Flue gas exit temperature (°C)	123	166	166	153
Boiler efficiency (%)	92.7	95.3	95.0	95.7

CFB technology provides solutions for reducing CO_2 emissions

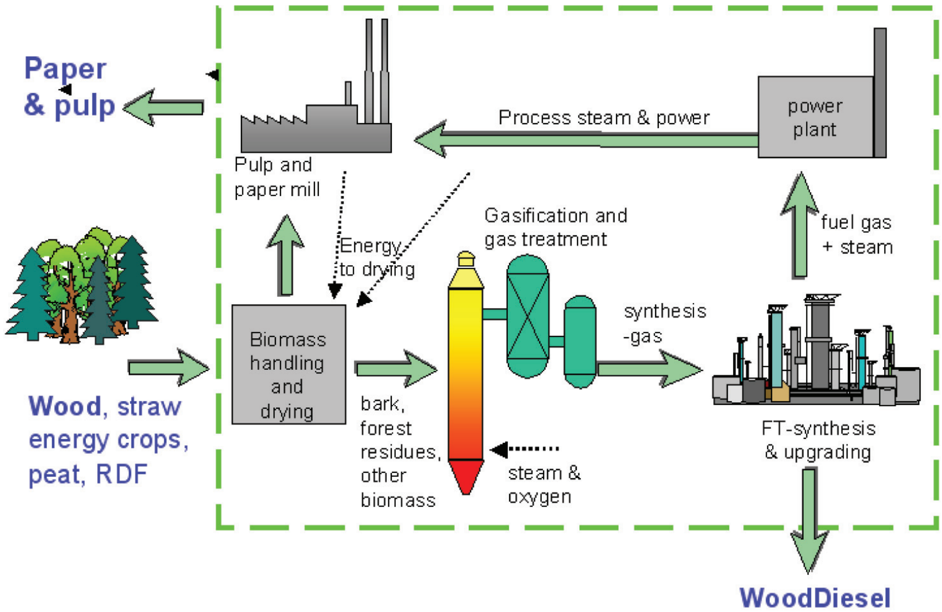


Figure 18—Finnish concept for biodiesel production from biomass

The Finnish development work is aimed at intermediate-size syngas plants that will be economically feasible at 200–300 MW fuel input, especially when integrated with energy-consuming plants of other industries, e.g. pulp and paper industries. The process was developed on a 500 kW-scale process development unit during the period 2005–2007. Long-term demonstration is currently projected for 2008–2010.

Conclusions

Circulating fluidized bed (CFB) boiler technology has developed to meet utility-scale requirements. Owning to high efficiency, excellent multi-fuel capability and low emissions of major pollutants (SO_2, NO_x, CO, CO_2, particulates, etc.) the technology offers reliable solution, for both repowering of old power plants or building a new plant. CFB technology has proved excellent with both low-grade fuels, such as lignite and low-grade bituminous coals, coal washing discards, and oil shale, and with good quality fuels. Co-combustion of various types of biomass and waste fuels in CFB boilers has proven an efficient and economic way to reduce CO_2 emissions and to minimize landfilling. CFB technology is today commercial for sizes up to 600 MWe with once-through supercritical technology and by the end of 2009 Foster Wheeler will be ready to offer 800 MWe CFB units.

Carbon capture and storage (CCS) offers the potential for major cuts in CO_2 emissions of fossil fuel-based power generation in the fairly short term. Oxyfuel combustion is one of the identified main CCS technology options. Foster Wheeler Global Power Group (FW) is developing its circulating fluidized bed (CFB) combustion technology for oxycombustion to provide a CCS-ready solution. The company is also developing a pressurized biomass gasifier to target the growing second generation biodiesel markets.

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