Update on lignite firing

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Abstract

Low rank coals have gained increasing importance in recent years and the long-term future of coal-derived energy supplies will have to include the greater use of low rank coal. However, the relatively low economic value due to the high moisture content and low calorific value, and other undesirable properties of lignite coals limited their use mainly to power generation at, or, close to, the mining site. Another important issue regarding the use of lignite is its environmental impact. A range of advanced combustion technologies has been developed to improve the efficiency of lignite-fired power generation. With modern technologies it is now possible to produce electricity economically from lignite while addressing environmental concerns. This report reviews the advanced technologies used in modern lignite-fired power plants with a focus on pulverised lignite combustion technologies. CFBC combustion processes are also reviewed in brief and they are compared with pulverised lignite combustion technologies.

Acronyms and abbreviations

CFB	circulating fluidised bed
CFBC	circulating fluidised bed combustion
CFD	computational fluid dynamics
CV	calorific value
EHE	external heat exchanger
GRE	Great River Energy
GWe	gigawatts electric
kJ/kg	kilojoules per kilogram
kWh	kilowatts hour
Gt	billion tonnes
FBC	fluidised bed combustion
FBHE	fluidised bed heat exchanger
FEGT	furnace exit gas temperature
FGD	flue gas desulphurisation
GJ	gigajoule
HHV	higher heating value
IDGCC	Integrated Drying Gasification Combined Cycle
IEA	International Energy Agency
IGCC	integrated gasification combined cycle
kg/h	kilograms per hour
kPa	kilopascals
kWh	kilowatts per hour
LHV	lower heating value
m^2	square metres
m^3/d	cubic metres per day
mg/m^3	micrograms per cubic metre
MJ	megajoule
MJ/s	megajoules per second
MPa	megapascals
Mt	million tonnes
MWe	megawatts electric
MWh	megawatts hour
MWth	megawatts thermal
O&M	operating and maintenance
OFA	over fire air
PC	pulverised coal
PCC	pulverised coal combustion
R&D	research and development
rmp	revolutions per minute
t/h	tonnes per hour
t/y	tonnes per year
SC	supercritical
WEC	World Energy Council
US DOE	The US Department of Energy
USC	ultra-supercritical
µm	micrometres

Contents

1 Introduction

Coal plays a significant role in meeting global energy demand. Coal is the world's most abundant fossil fuel and coal deposits exist in nearly every region of the world. Therefore, coal has an enormous geostrategic advantage compared to crude oil and natural gas and is vital for global energy security. Since 2000, global coal consumption has grown at an average annual rate of 4.9%, faster than any other fuel. The increase in coal use is set to continue and is expected to rise by over 60% by 2030, with developing countries accounting for around 97% of this increase (WEC, 2010). The main driver of demand for coal is the inexorable growth in energy needed for power generation. The recent World Energy Outlook by the International Energy Agency (IEA, 2009) projected that the world electricity demand would grow at an annual rate of 2.5% between 2007 and 2030. Globally, additions to power generation capacity could total 4800 GW by 2030. A significant portion of the electricity generated will come from coal-fired power plants. Coal is, and will remain, the major fuel of the power sector. The current share of coal in the global power generation mix is approximately 41% and it is expected to increase to 44% by 2030 (IEA, 2009).

The quality of coal varies significantly depending on the degree of metamorphism from peat to anthracite (this is referred to as the 'rank' of the coal) and the geographical location where the coal has formed. Generally, the term 'coal' refers to a whole range of combustible sedimentary rock materials spanning a continuous quality scale. Coal is usually divided into four main categories: anthracite, bituminous, subbituminous and lignite/brown coal. Lignite and subbituminous coals are classified as low rank coals. However, there is no single universally accepted coal classification system for use at an international level and a range of different definitions and categorisation systems apply in different parts of the world. Detailed descriptions of these systems can be found in a report published earlier by The IEA Clean Coal Centre (IEA CCC) (Carpenter, 1988). The International Coal Classification of the Economic Commission for Europe (UN/ECE) recognises two broad categories of coal: hard coal and brown coal. According to UN/ECE hard coal is defined as a coal with gross calorific value (CV) of >5700 kcal/kg (23.9 MJ/kg) on an ash-free but moist basis and with a mean random reflectance of vitrinite of at least 0.6. Hard coal is calculated as the sum of coking coal and steam coal. Brown coal comprises:

- subbituminous coal, which is defined as non-agglomerating coal with a gross CV between 4165 kcal/kg (17.4 MJ/kg) and 5700 kcal/kg (23.9 MJ/kg) containing more than 31% volatile matter on a dry mineral matter free basis;
- lignite, which is non-agglomerating coal with a gross CV <4165 kcal/kg (17.4 MJ/kg) and volatile matter >31% on a dry mineral matter free basis.

Coal was the first fossil fuel to be used on an industrial scale and it remains an essential part in world energy mix. Many countries view their indigenous coal resources as an essential element of their plans for national economic development and security. Countries such as China, the USA, India, Australia and South Africa rely on domestic supplies of coal for their energy needs. However, many coal-producing countries have witnessed a steady decline in the quality of the coal produced for decades. Centuries of active coal extraction has resulted in a depletion of reserves of higher grade coals and a growing reliance on reserves of lower quality coals. This trend is particularly apparent in many of the long-industrialised countries, where significant coal production may have been taking place for centuries but it is also observed in some developing countries. In many countries such as Turkey, Greece, Germany and many Central and Eastern European countries, coal reserves are predominantly of lignite/brown coals and it is considered that domestic lignite will remain an indispensable domestic source of energy for many years in these countries. There has been a sharp fall in the reserves-to-production ratio of hard coal due to the rapid growth in hard coal production worldwide resulting in price surges and supply risks, which pose the key challenges to many coal-consuming countries. Besides, all the major exporting countries are experiencing a combination of logistical or production constraints. China, for example, was a net coal exporter with exports peaking at 87 Mt in 2001, but net exports have declined consistently since then, due to the strong growth in domestic demand, and China may soon become a net coal importer. Many coal consuming countries are forced to consider how to secure energy supplies and use domestic sources more effectively. As a result, the long-term future of coal-derived energy supplies will have to include the greater use of low rank coal, a trend that can already be seen in many parts of the world. The international market is beginning to accept coals with lower heating value, and low rank coals have gained increasing importance in recent years. It is forecast that the use of lignite will grow at an average rate of ~1%/y and will reach 1.2 Gt/y by 2030 (WCI, nd). The global reserves of low quality coal are reviewed by Mills (2011) and the utilisation of low rank coals is described by Dong (2011).

When considering the use of lignite one very important question that has to be answered is whether it is economic to use it. The economic value of lignite is relatively low compared to hard coal due to its low CV and other undesirable properties that limit its use in conventional coal utilisation equipment. Also, the high ash/moisture content of lignite makes its long distance transport very costly and increases overall environmental impacts. Consequently, the use of lignite has been, in the past, limited to power generation at, or close, to the mining site. Another important issue regarding the use of lignite is its environmental impact. These days, proposals to build coal-fired power plants are often strongly opposed by local residents and non-government organisations (NGO) because of concerns over the impact of coal combustion on the environment and climate change. Using lignite as a fuel for power generation has several disadvantages. The low heating values and high moisture content of lignite, for example, imply larger boiler size and low energy efficiency when used directly in power plants. The main combustible component of lignite or coal consists largely of carbon and therefore coal/lignite has a higher carbon content per embedded unit of energy than other types of fossil fuels. Lower efficiency of lignite combustion means not only reduced economic values of lignite but also that more CO_2 is released into the atmosphere for each kilowatt-hour of electricity generated. In addition, the low quality of lignite translates into undesirable properties so its use in coal boilers, gasifiers or other equipment may cause operational difficulties. However, technologies have advanced significantly and viable, highly effective technologies are now available to mitigate the environmental impacts of coal-fired power plants for a range of pollutants such as emissions of particulates, SO_2, NOx and mercury. A key strategy in the mitigation of environmental impacts of lignite-fired power plants is to improve energy efficiency. A range of advanced combustion technologies has been developed to improve the efficiency of lignite-fired power generation. Today's state-of-the-art lignite-fired power plants in operation in Germany have achieved energy efficiencies as high as 43%, putting lignite plants in a similar position as modern hard coal based power plants. With modern technologies it is now possible to produce electricity economically from lignite while addressing environmental concerns.

This report reviews the state-of-the-art technologies for efficient lignite combustion for power generation. It begins with a brief description in Chapter 2 of the background of lignite production and utilisation. The global lignite reserves, productions and consumption are reviewed. The characteristics of lignite and the diverse nature of lignite found worldwide are discussed in brief. The current status of lignite utilisation in power generation is also presented in the chapter.

The efficiency of lignite-fired power plants can be improved by removing the coal moisture prior to utilisation, by improving the power generation cycle efficiency, or by a combination of these approaches. Chapter 3 discusses lignite drying technologies. This chapter focuses on the recent developments in advanced lignite pre-drying technologies applicable to power plants. The operation of modern lignite-fired power plants in Germany has proved that lignite can be burned efficiently and with good environmental performance, producing electricity at competitive prices. RWE's BoA plants have achieved net plant efficiencies of >43% (LHV based), by application of advanced technologies in combination with improved engineering designs to all parts of the power plant. Chapter 4 reviews the boiler design concepts for modern pulverised lignite fired power plants. The selection of milling system, the advances in burner designs and arraignments, the design concepts for a state-of-the-art pulverised lignite fired steam generator are described in detail here. Other technical advances in system and process engineering that contribute to the increased energy efficiency of lignite plants such as improved turbine design, efficient waste heat recovery and utilisation, the advances in boiler and turbine materials that lead to the adoption of high efficiency supercritical steam cycles are also presented and discussed in Chapter 4. The impact of lignite quality on the design, operation and performance of the plant is examined. And finally, a case study of the newly-commissioned BoA plants is performed.

Circulating fluidised bed combustion (CFBC) has emerged as a viable alternative to pulverised coal combustion technology for power generation. CFBC technology is capable of burning a diverse range of fuels and is particularly suited to low grade fuels. Recent developments and advances in CFBC technologies are reviewed in brief and a comparison of CFBC with PCC is outlined in Chapter 5. The major CFB manufacturers, the main features of their CFB technology and the applications in lignite- and coal-fired power plants are also discussed in Chapter 5. And finally, a summary is given in Chapter 6.

This study focuses on the modern pulverised lignite combustion technologies. Advances and improvements in the process and engineering designs in other parts of lignite-fired power plants that contribute to the efficiency gain are also examined in the study.

2 Lignite and its utilisation

Lignite is a soft fuel and is often referred to as brown coal due to its brownish-black colour. It is considered the lowest rank of coal. Lignite has a low carbon content of around 25–35%, a high inherent moisture content sometimes as high as 70%, and an ash content ranging from 6% to 19%. The low energy density and typically high moisture content makes long-distance transport of lignite costly and therefore, international trade of lignite is essentially nonexistent. The use of lignite has been limited mainly to power generation at, or close to, the mining site (minemouth power plants).

2.1 Reserves and production

Coal deposits are available in almost every country worldwide, with recoverable reserves in around 70 countries. Around half of the world's estimated recoverable coal reserves comprise low value coals, predominantly lignites, subbituminous coals, and high-ash bituminous coals. Proven recoverable coal/lignite reserves, in general, refer to those quantities that geological and engineering information indicates with reasonable certainty can be recovered in the future from known deposits under existing economic and operating conditions. It should be borne in mind that definitions, methodology, terminology and conventions of coal ranks/classification differ widely from country to country.

Table 1 Lignite reserves, Mt

Country	Proved recoverable lignite		Total lignite, WEC
	Mills, 2011	WEC, 2010	
Canada	2,236	2,236	6,582
Ecuador		24	24
Mexico	51	51	1,211
USA	30,374	30,176	237,295
Total America	32,661	32,487	257,779
China	18,600	18,600	114,500
India	4,258	4,500	60,600
Indonesia	798	1,105	5,529
Japan		10	350
Kazakhstan	3,130	12,100	33,600
Kyrgyzstan		812	812
Laos		499	503
Mongolia		1,350	2,520
Pakistan	1814	1,904	2,070
Philippines		105	316
Thailand	1,354	1,239	1,239
Turkey	1,814	1,814	2,343
Uzbekistan	2,000	1,853	1,900
Total Asia	33,768	45,891	228,264
Albania	794	794	794
Belarus		100	100
Bosnia-Herzegovina		2,369	2,853

Therefore, the estimates from different sources of coal or lignite reserves and production, especially the breakdown for any particular country or region, vary and should be regarded as indicative only.

According to the 2010 Survey of Energy Resources by World Energy Council (WEC, 2010), the world total proven recoverable coal reserves at the end of 2008 amount to some 860 Gt, of which 195 Gt (23%) is lignite. Mills (2011) estimates the world's total proven recoverable coal reserves to be higher, between 1019 and 1025 Gt, of which 18% is lignite. Mills suggests that the global total proven reserves of lignite stand somewhere between 149.8 Gt and 283.2 Gt. Michel (2008) suggests that lignite resources in countries with largest deposits such as Russia, USA, Canada, Australia, and Germany could be more than 6000 Gt. Depending on the prevailing prices for competing fuels, several per cent to as much as 50% of these resources might be economically feasible to recover. The estimates by WEC and Mills for the regional and global lignite reserves are shown in Table 1. The total proven recoverable coal reserves in these regions are also given in the table for comparisons. The regional proven recoverable coal reserves by rank are shown in Figure 1.

Based on Mills' estimates, regionally (on a tonnage basis), lignite makes up about 14% of American coal reserves, 15% of Asian, 18% of European, and 48% of Australian. It can be seen from Table 1 in many countries such as Pakistan, Thailand, Turkey, Uzbekistan and many European countries that lignite is the main or in some cases the only indigenous coal reserve.

For countries with lignite reserves, a particular advantage of its use as a source of energy is that it

Table 1 –- continued

Country	Proved recoverable lignite		Total lignite, WEC
	Mills, 2011	WEC, 2010	
Bulgaria	1,928	2,174	2,366
Czech Republic	211	908	1,100
Germany	6,556	40,600	40,699
Greece	3,900	3,020	3,020
Hungary	2,933	1,208	1,660
Macedonia (Republic)		332	332
Poland	1,490	1,371	5,709
Portugal		33	36
Romania	1,364	280	291
Russia	10,450	10,450	157,010
Serbia	13,500	13,400	13,770
Slovakia		260	262
Slovenia		199	223
Spain	30	30	530
Ukraine	1,945	1,945	33,873
Total Europe		79,473	265,027
Australia	37,400	37,200	76,400
New Zealand	333	333	571
Total Oceania	37,733	37,533	76,973
Central African Rep.		3	3
Total Africa		3	31,692
Total World		**195,387**	**860,938**

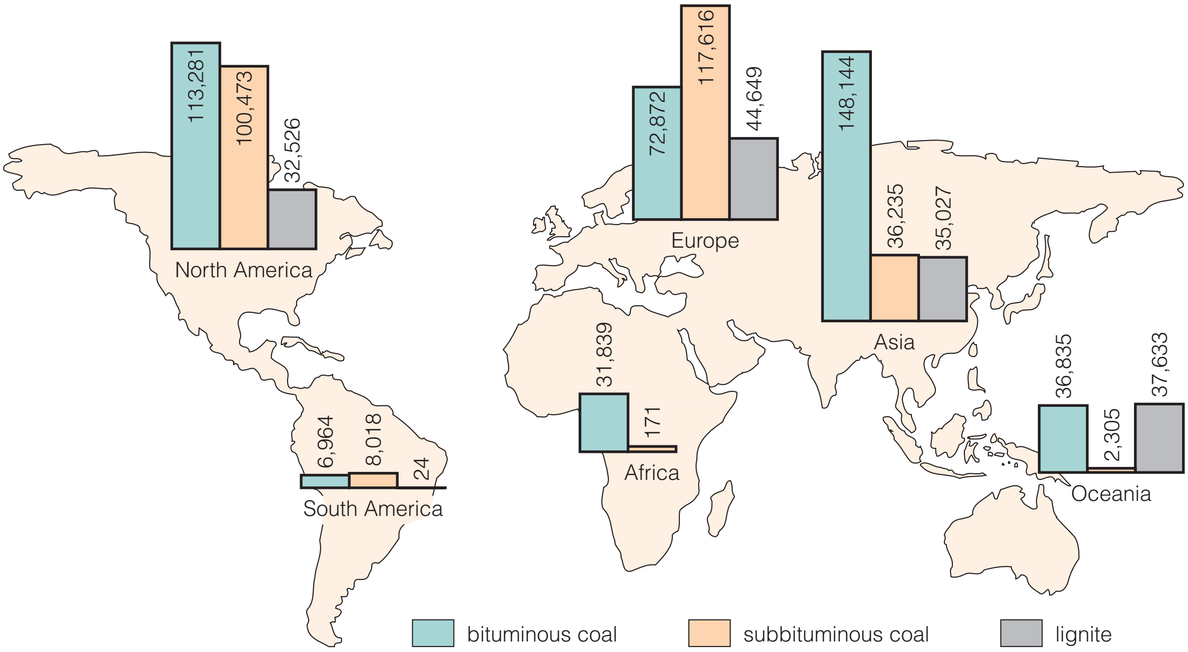


Figure 1 Regional coal reserves by rank, Mt (Chakraborty and others, 2009)

usually offers very high security of supply. Lignite is usually produced by surface mining, which keeps extraction costs much lower than hard coals that are extracted through underground operations. However, despite the similarity in global reserves of low-rank and hard coals, the individual consumption and production trends are quite different. The world consumes much more hard coal than lignite/brown coal and the gap between the two has become wider over the years. Although coal has been a fast growing fuel in the past decade the increases are mainly observed in hard coal consumption and production, whilst the consumption and production of lignite/brown coal remain stable. Globally, lignite production peaked at 1189 Mt in 1990. Since then, production has been stable, varying slightly between 913 and 956 Mt/y (OECD/IEA, 2009). In 2009, the total global hard coal production was estimated to be 5990 Mt, which was 3.4% more than the 5794 Mt produced in 2008. Global lignite/brown coal production for the same period decreased by 5.4%, from 965 Mt in 2008 to an estimated 913 Mt produced in 2009 (WCI, 2010). It is predicted that without a corresponding increase in hard coal reserves, which are likely to become more difficult and more expensive to exploit than previously, global reserves of hard coals will be exhausted much sooner than those of lower quality coal (Kavalov and Peteves, 2007). Consequently, production of lignite/brown coal is forecast to grow at an average annual rate of around 1% and will reach 1.2 Gt/y by 2030 (WCI, nd). In recent years, individual national growth rates have varied between zero and 2%/y.

Currently, twelve countries each produce more than 20 Mt/y of lignite. Germany remains the world's largest lignite/brown coal producer. In 2008, the world's eight biggest lignite producers comprised Germany, Turkey, Russia, the USA, Australia, Greece, Poland and the Czech Republic. Apart from the world top producers, there are also many countries where output is less, but nevertheless important in respective national energy mixes (Mills, 2011). Table 2 gives the regional and world total lignite production in 2008. Figure 2 shows the output of the major lignite producers in 2000 and 2008. It can be seen from Figure 2 that since 2000, lignite output has fallen in countries such as Hungary and Canada, whereas it has increased in Australia, Indonesia, Turkey, Serbia, Romania, India and Bulgaria. In 2009, lignite production in Germany decreased by around 2.9% compared to its production level in 2008 whilst it increased slightly in Canada and India (WCI, 2010). Case studies of the reserves, production and use of lignite in different countries can be found in a recent report by Mills (2011).

More than 90% of global lignite production is from opencast mines although the underground mining

Table 2 **Regional and global total lignite output in 2008** (WEC, 2010)		
Country	Lignite production, Mt	Total coal production, Mt
Canada	9.9	68.1
Chile	0.3	0.5
USA	68.7	1061.8
Total America	78.9	1228.8
China	66	2,782
India	32.1	515.8
Kazakhstan	4.6	104.9
Kyrgyzstan	0.3	0.4
Mongolia	9.6	9.8
Myanmar (Burma)	0.3	0.3
Pakistan	0.9	3.9
Thailand	18	18
Turkey	76.2	78.8
Uzbekistan	3.0	3.1
Total Asia	211.0	3829.5
Bosnia-Herzegovina	11.2	11.2
Bulgaria	26.1	28.8
Czech Republic	47.9	60.1
Germany	175.3	194.4
Greece	65.7	65.7
Hungary	9.4	9.4
Macedonia (Republic)	7.3	7.3
Montenegro	1.7	1.7
Poland	59.7	144.0
Romania	32.4	35.2
Russia	80.5	326.5
Serbia	36.9	37.4
Slovakia	2.4	2.4
Slovenia	4.0	4.5
Ukraine	0.2	59.7
Total Europe	560.7	1020.4
Australia	65.5	397.6
New Zealand	0.2	4.9
Total Oceania	65.7	402.5
Total World	**916.3**	**6739.2**

of lignite has been carried out on a significant scale in countries of the former Yugoslavia, in Austria and other places (Couch, 2004).

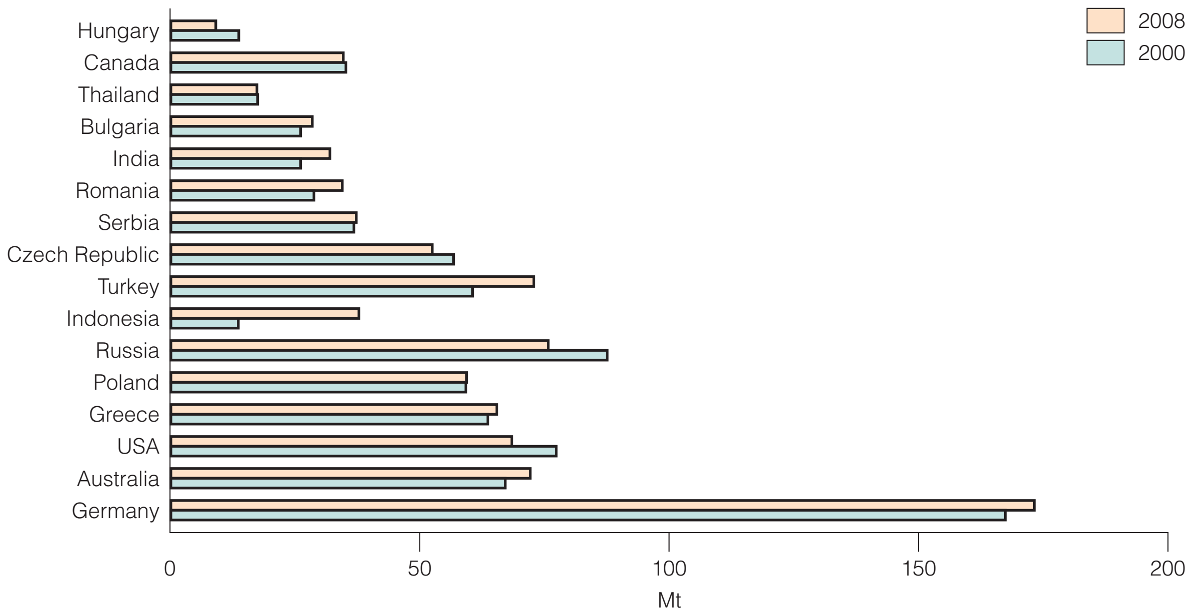


Figure 2 Lignite production of the major producers in 2000 and 2008 (OECD/IEA, 2009)

2.2 Lignite characteristics

Lignite is a coal in the early stages of coalification, with properties intermediate to those of bituminous coal and peat. Lignite has a high inherent moisture content and a low energy content. In general, lignite is any variety of coal that contains:

- less than 70% water (which distinguishes it from peat);
- 60% to 70% of carbon on a dry- and ash-free basis;
- a calorific value lower than 17 MJ/kg.

One notable characteristic of lignites from different reserves the world over is the marked variability in properties. Some (such as lignite from Australia) can have a very high moisture content. Others (such as those in Greece, Romania and Turkey) may contain >35% moisture, but also have >25% ash. Some may have a very low sulphur content, whereas others may be much higher (such as those from Bulgaria and Thailand) (Couch, 2004). Even within the same deposit, variation in ash, moisture, volatile matter and sulphur content of the lignite is generally much greater than is normally observed in hard coal deposits. Some of this variability can be attributed to the lignite coals being geologically quite ‘young’ and inhomogeneous. The properties of lignites from different countries are shown in Table 3. As a result of this variability, and because there are also substantial variations in the quality of the lignite mined from a particular deposit, the correct design of equipment for lignite use is even more important than it is for the use of a more consistent bituminous coal.

Lignite coals are susceptible to spontaneous combustion, which can give rise to transport, storage and handling problems. In spite of the generally high moisture content of lignite coals, the organic matter is inherently more reactive than in older coals. When lignite is stacked, and air can reach the middle of the stockpile, oxidation takes place, thus raising the temperature. In a stockpile, this heat may not be able to escape, and in the warmer environment, the reaction rate of the oxidation increases. If the pile is left for long enough and air can percolate into it, then in extreme situations it can catch fire, uncontrollably. In order to minimise the risk of spontaneous combustion, some mine operators transport the lignite from where it is mined straight to the power plant with a minimum of intermediate storage/stocking. The amount of lignite held as a buffer in hoppers might amount to just a few hours of operation of the power plant boilers.

Table 3 Properties of lignites from different countries (CoalPower; WEC, 2004, 2007; Couch, 2004; Euracoal and individual national sources)

Country	Moisture content, % as-mined	Ash content, % db	Sulphur content, % db	CV, MJ/kg LHV
Australia	46–70	1–7.4	0.28–1.74	9.8–15.2
Bulgaria	23–56	20-48	0.9-7.0	6.7–15.0
Canada	32–41	8–25	0.3–1.1	10.6–17.0
Chile	10	14.4	0.9–1.0	
China	19.6–50	8.6–40	0.2–4.7	9.0–13.3
Colombia	17	25	0.7	16.8
Czech Republic	9.6–55.0	10–40	0.37–6.0	9.0–20.0
Germany	40–63	1–53	0.15–3.6	6.7–15.0
Greece	41–65	3.5–25	0.3–1.0	5.0–11.0
India	6–55	5–48	1.5–4.5	10.0–12.0
Indonesia	35–75	1–15	0.1–2.4	<17.4
Kosovo	35–50	12–21	<1.0	5.8–8.4
Laos			0.7–1.1	8.0–10.0
Malaysia	15–25	4–18	0.05–0.3	4.5–6.2
Myanmar	9.7	8.9	0.93	
New Zealand	38.0–45.0	5.0–30.0	0.3–4.6	13.0–19.0
Philippines	55–60	15	0.3–0.6	9.5
Poland	50–55	5–11	0.59	5.0–10.3
Romania	40–43	30–40	1.2	7.0–8.6
Russia	16.5–58	8.4–45	0.3–7.7	6.0–15.0
Serbia	43–55	18–25	0.5–0.9	6.8–7.5
Spain	8–50	14–70	1.2–>9.0	7.0–17.0
Slovenia	36	14	1.4	11.3
Slovakia	15.2–33.9	20.7–33.9	1.4–2.0	10.7–11.6
Thailand	12–49	10–55	10.5	5.0–10.0
Turkey	10–60	10–56	0.2–4.7	4.6–22.3
USA	30–44	4–20	0.2–1.4	5.0–17.4
Ukraine	30–40	29–46	Up to 3.3	12.4
Vietnam		20–40	2.5–6.2	10.4–18.4

Under some national categorisation systems, some examples may be considered as subbituminous coals

2.3 Lignite utilisation

Due to the combination of high moisture content (high transport costs) and high reactivity (risk of spontaneous combustion) lignite coals are used close to the mine, and they are used almost exclusively for power generation. The majority of existing lignite power stations are pulverised coal fired steam cycle plants. Lignite-fired fluidised-bed boilers have also been installed in many parts of the world and are in operation now. Subcritical lignite combustion plants still dominate lignite-based power generation. The majority of existing subcritical plants is based on the conventional single reheat thermal cycle.

Supercritical steam generators have been developed rapidly and deployed over the past decades. Currently, Germany possesses the most advanced lignite-fired supercritical pulverised-lignite combustion technologies and it has the world's largest and most efficient lignite-fired power plants in operation.

Lignite-fired power plants are found in operation in Asia, many parts of Europe and in Canada and the USA. Today, there are around 450 lignite-fired power generating units installed worldwide with a total capacity of over 104 GWe. More than 30 lignite-fired units with a capacity of over 14 GWe are currently under construction or are planned to be built (IEA CCC, 2011). Many of the existing units are rather old and some are approaching the end of their service life. There is a need for these units to be upgraded, repowered or replaced by new power plants. The power producers will need to assess the best available technologies and select the options most suited to their preferred coal types, unit sizes, local conditions and national compliance requirements. There are currently two competing technologies for lignite firing: pulverised coal and CFB combustion. The following chapters will provide details of the advanced technologies and the recent technical innovations and improvements in system and engineering designs of the two combustion processes.

3 Lignite drying technologies

The high moisture content of lignite is a major issue in its commercial utilisation. In conventional (existing) pulverised lignite fired power plants, a significant amount of the energy in the coal is absorbed as heat to evaporate the water before any useful energy can be obtained and converted to electricity. This leads to low thermal efficiency, high CO_2 emissions per unit of energy output and high capital costs of a plant. Figure 3 shows the thermal efficiency of a power plant as a function of coal moisture content. Other technical difficulties that arise from high moisture content include fuel handling problems, difficulty in achieving ignition, and larger boiler size required due to the increased flue gas volumetric flow. Therefore, drying of coal prior to combustion is important to improve thermal efficiency and consequently reduce CO_2 emissions. Table 4 compares the efficiency gains of a modern supercritical power plant through lignite pre-drying and the corresponding reductions in CO_2 emissions.

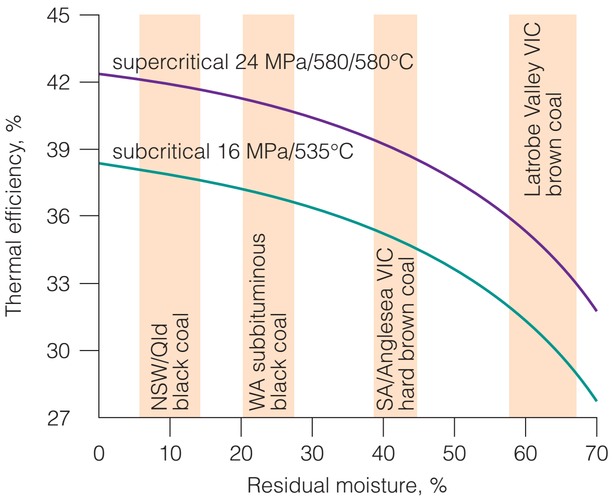


Figure 3 Power plant thermal efficiency as a function of moisture content of coal (Wibberley and others, 2006)

A large number of technologies for the removal of water from lignite coals have been developed or are under development. These technologies broadly fall into two categories: evaporative drying and non-evaporative dewatering processes. In the evaporative processes the moisture is transformed into the gaseous phase (as steam) during the course of drying, whereas in the non-evaporative processes the moisture is removed as a liquid. Drying the fuel imposes an energy penalty on the system. In evaporative drying, not only is there latent heat (approximately 2.4 MJ/kg for water) involved, there is also the sensible heat of the solids present. Since most evaporative processes involve no heat recovery, the energy requirement is broadly in the range of 3.0 to 4.5 MJ/kg of water removed. The energy penalty for non-evaporative processes is generally less severe since the latent heat of vaporisation is avoided, and the energy requirement is typically between 1.0 to 2.5 MJ/kg of water removed (Couch, 1990). Non-evaporative processes also have the advantage that soluble inorganic constituents in the coal (which contribute to boiler fouling) are removed in proportion to the extent of water removal, thus improving coal quality. In view of the high moisture content, drying is an energy-intensive process, and that is why energy efficiency is a primary focus here. Obviously, it is important that the most energy efficient and cost effective drying route is used. Detailed descriptions of conventional

Table 4 Typical efficiencies and CO_2 emissions of pulverised lignite fired power plants (Brockway, 2007)

Technology	Efficiency, %, HHV net	CO_2 emissions, kg/MWh net
Existing plants	28	1250
New SC plant (raw coal feed)	34	1000
New SC plants (dried coal feed, 50% water removal from raw coal)	39	850
New SC plants (dried coal feed, 70% water removal from raw coal)	41	820
IGCC (dry coal feed)	45	720

drying processes can be found in earlier publications (Couch, 1990; Li, 2004; Wibberley and others, 2006; Nunes, 2009; Katalambula and Gupta, 2009). This report will focus on the latest development of more advanced drying technologies.

3.1 Evaporative drying

3.1.1 WTA technology

WTA is an abbreviation in German for ‘fluidised bed drying with internal waste heat utilisation’. Developed by RWE (Germany), the WTA technology is based on evaporative drying in a stationary fluidised bed with low expansion. The energy required for drying is supplied via a heat exchanger that is integrated in the fluidised-bed dryer and heated with steam. Drying takes place in virtually 100% pure steam which is slightly superheated. At constant pressure, equilibrium between the steam temperature and the residual moisture of the dried lignite is reached depending on the steam temperature. By controlling the fluidised-bed temperature, the moisture content can be adjusted and kept constant at the desired value. For example, at a system pressure of approximately 0.11 MPa, a residual moisture content of ~12% is achieved with German lignite at a temperature of 110°C and with Australian lignite at 107ºC (RWE, 2008).

The WTA process has two variants in design: the closed cycle and the open cycle, as shown in Figure 4. The two variants differ in that the steam providing the heat comes from an external source (open cycle) or is the evaporated moisture from the raw coal (closed cycle). In closed cycle, the WTA plant is installed downstream of raw-lignite milling and integrated with a mechanical vapour compressor to allow the vapour energy to be used in the drying process. Following cleaning in an electrostatic precipitator, the evaporated coal water (fuel-laden vapour) is recompressed to about 0.4 MPa in a compressor, so that the vapour can be used to heat the heat exchanger installed in the dryer. The sensible heat of the produced vapour condensate is used to preheat the raw lignite to about 65–70ºC and, hence, contributes significantly to meeting the dryer’s energy demand. Part of the cleaned vapour is recycled back to the dryer to fluidise the bed. The dried coal is cooled and, where required, milled a second time to a grain size of 0–1 mm in a mill integrated in the WTA plant to make it directly suitable for combustion in the power plant. In open cycle, the WTA plant is installed downstream of raw-lignite milling and upstream of vapour condensation. The heat needed for drying of the coal is provided by hot steam extracted from the low pressure part of a steam turbine in an adjacent power plant. The vapour coming from the WTA dryer can be used to preheat the boiler feedwater in a power station’s water-steam cycle. The vapour condensate produced from the WTA process can be used as water in industrial processes. The selection of the vapour utilisation variant depends, among other things, on the drying task and the integration into the overall process.

The WTA drying process has been developed for two different input grain sizes: The so-called coarse-grain WTA plant operates with input coal grain sizes between 0 mm and 6 mm, while the fine-grain WTA process uses grain sizes of 0 mm to 2 mm. For pulverised coal combustion (PCC) power plants, the fine-grain variant is usually the more attractive option in technical and economic terms. When the finer grain size of raw coal is used the amount of vapour needed for fluidisation in the dryer is reduced by about 70% compared with coarse grain coal. Furthermore, use of fine grain coal increases the heat transfer efficiency by about 80%, leading to a significant reduction in the size of the equipment and components needed. For example, the volume of the dryer can be reduced by almost 70%. In addition, the drying in the fluidised bed further reduces the grain size and the dry coal leaving the dryer has a grain size of typically less than 1 mm, making it suitable for immediate use in the steam generator.

The main advantages of the WTA technology include (RWE, 2008):

- high energy efficiency and reduced emissions due to drying at low temperatures, recovery and use of the latent heat of evaporation of the evaporated coal water and use of the steam;

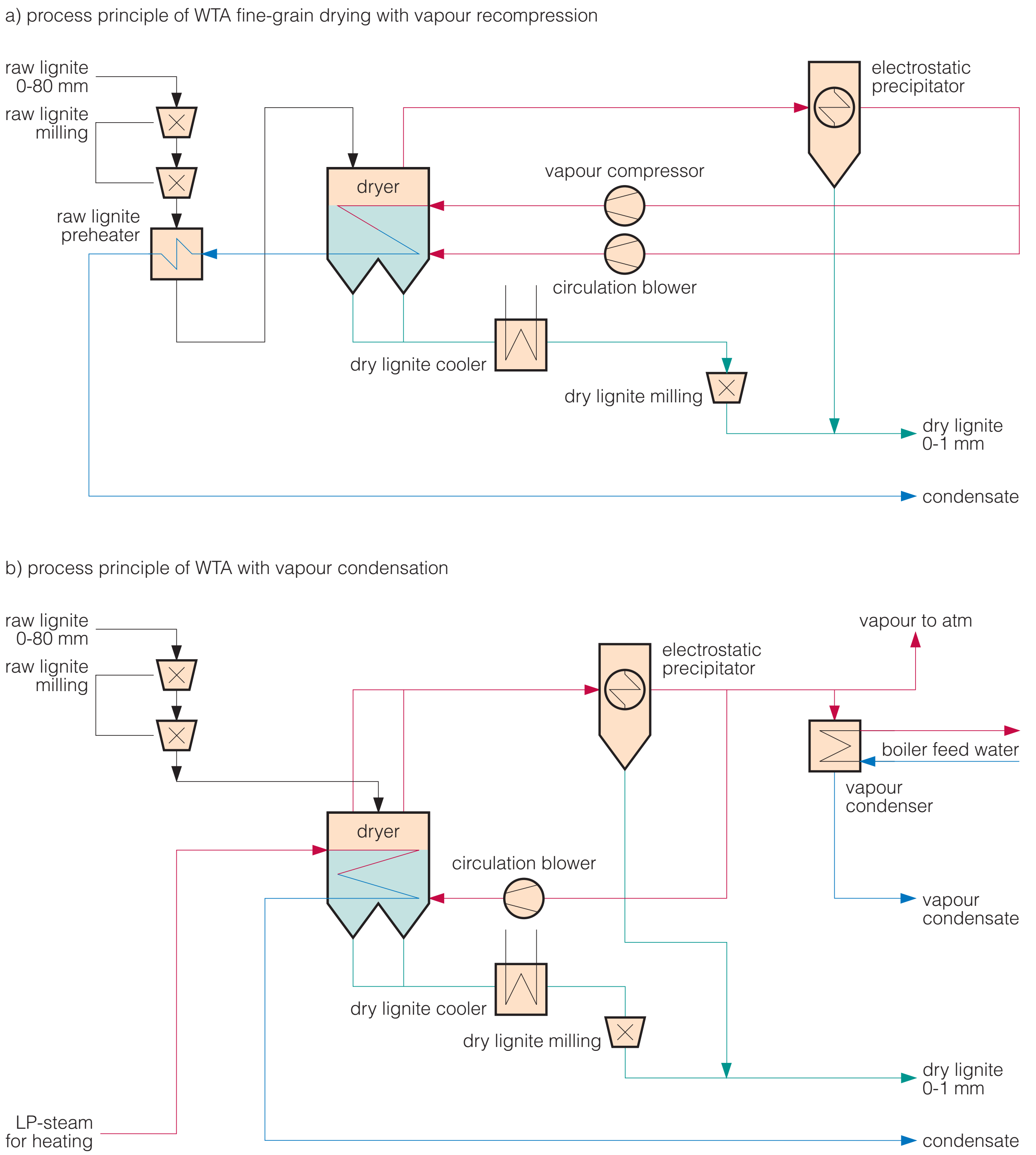


Figure 4 WTA process with closed and open cycle (RWE, 2008)

- high drying capacity per dryer unit;
- compact design;
- safe plant operation as drying takes place in an inert atmosphere (avoidance of explosive coal dust mixtures);
- flexibility to drying task.

The fine-grain open cycle variant was chosen for the first pilot WTA plant at RWE's lignite-fired Unit K at Niederaussem power plant. This fully-assembled WTA system enables 30% of the firing capacity to be supplied by dried lignite, equivalent to around 210 t/h (or 110 t/h of dry lignite), ensuring that meaningful experience of dry lignite combustion is gained.

With a WTA process, depending on the drying variant and the moisture content of the raw lignite, the overall efficiency of a power plant may be increased by four percentage points. Investment costs are not expected to increase compared with conventional lignite-fired power plants because the additional costs associated with the dryer are almost offset by the savings in the boiler island (elimination of raw coal bunkers, beater wheel mills and flue gas recirculation ducts for drying purposes) and reduction in the flue gas path, including flue gas cleaning, which is lessened because of the smaller flue gas volume and the efficiency increase (Stamatelopoulos, 2007). RWE is currently commercialising its WTA process.

3.1.2 DryFining™

DryFining™ is a lignite fuel enhancement system that both dries and beneficiates raw lignite coals. Developed in the USA by a team led by Great River Energy (GRE), DryFining™ is a process that uses waste heat from the power plant to evaporate a portion of the fuel moisture from the lignite feedstock in a fluidised-bed coal dryer before it is fed into the boiler. Typically, about 45% of the fuel heat generated by a conventional pulverised coal fired power plant is lost in the condenser, and another 20% exits the stack. The DryFining™ exploits this heat, which otherwise has little use because of its low quality. Heated air is used as heating and fluidising medium in the dryer. Figure 5 provides a simplified flow diagram of the DryFining™ process. Warm cooling water from the turbine exhaust condenser goes to an air heater where ambient air is heated before being sent to the fluidised-bed coal dryer. The cooling water leaving the air heater is returned to the cooling tower. A separate water stream is passed through coils in the fluidised-bed coal dryer (a multi-stage dryer is used to enhance heat transfer). The purpose of these coils is to provide additional heat to the fluidised bed to reduce the amount of air required. The dried coal leaving the fluidised bed is sent to a pulveriser and then to the boiler. Air leaving the fluidised bed is cleaned of dust before being discharged into the atmosphere.

Funded by the US DOE as one of the Clean Coal Power Initiative projects, tests of DryFining™ on a prototype fluidised-bed coal dryer with a capacity of 115 t/h were carried out at Unit 2 of GRE's Coal Creek Station in Underwood, North Dakota, in 2006. The test results showed that pre-drying coal with DryFining™ not only reduced the moisture content of the coal resulting in improved boiler efficiency

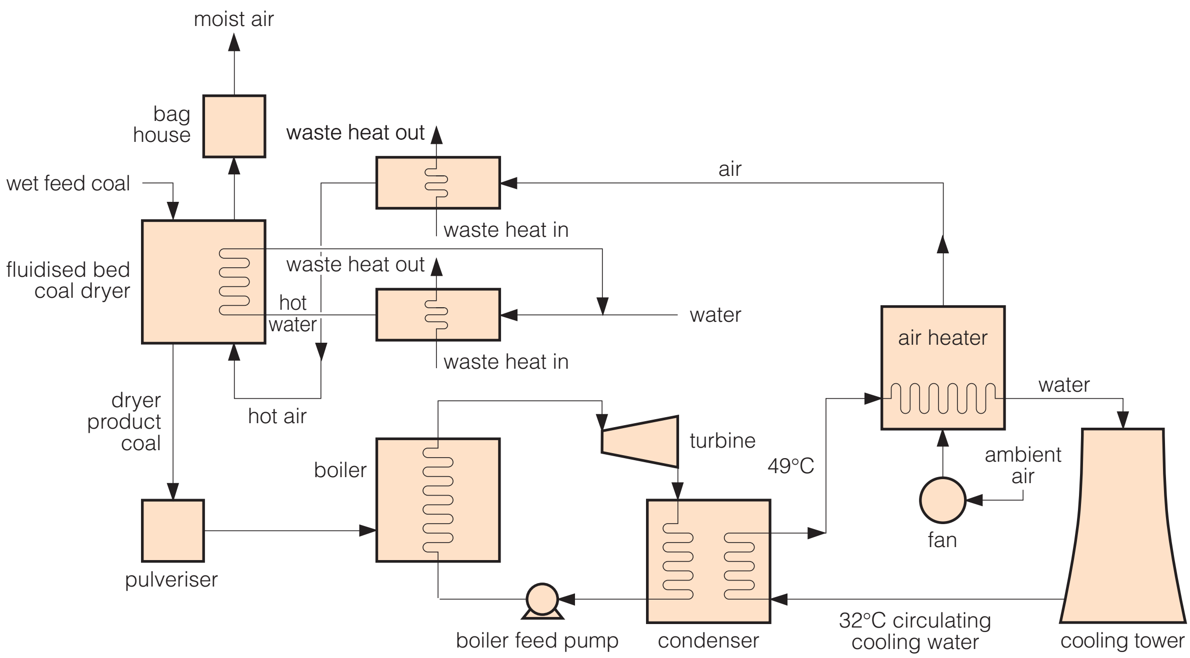


Figure 5 Schematic of DryFining™ process using waste heat from condenser water and flue gas (NETL, 2007)

and unit heat rate, but the emissions of SO_2, CO_2, NOx and particulate were also reduced. Encouraged by the results and having recognised the economic benefits of this technology in previous trials, GRE decided to go beyond the scope of the second phase of the US DOE project to demonstrate the technology at commercial scale at Unit 2 and self-funded another installation of four dryers on Unit 1. Controlled tests with wet and dried lignite were conducted in March/April 2010 after the commercial coal drying system was commissioned (NETL, 2007; Bullinger and Sarunac, 2010). GRE is now ready to commercialise this technology.

3.1.3 Entrained flow drying

This is the drying system integrated into the IDGCC (Integrated Drying Gasification Combined Cycle) process that is being developed by HRL in Victoria, Australia. Entrained flow drying has also been proposed as a low-cost stand-alone dryer. In the IDGCC process, the hot gas from an air-blown fluid bed gasifier is used to pre-dry the coal in an entrained flow dryer through direct contact under pressure. The feed coal is pressurised in a lock hopper system and then fed into the dryer where it is mixed with the hot gas leaving the gasifier. The heat in the gas is used to dry the coal whilst the evaporation of the water from the coal cools the gas without the need for expensive heat exchangers. The coal dryer is smaller and cheaper to build than conventional coal dryers because it operates under pressure.

3.1.4 Superheated steam drying (SHSD)

The use of superheated steam drying has a number of advantages such as reduced risk of spontaneous ignition/fire due to the absence of oxygen, increased drying rates and energy efficiency, reduction in dust emissions, and improved grindability. It was also observed that the sulphur and sodium content of lignite coals could be reduced during superheated steam drying above 300ºC. A desulphurisation rate of between 40% and 50% at steam temperatures between 300ºC and 500ºC was reported. In general, the pure superheated steam environment primarily reduced the inorganic sulphur content of the coal. However, steam processing environments that had a small amount of air did provide significant reductions in the organic sulphur content as well. Depending on the type of coal and the steam temperature, the sodium content of the coals could be reduced by 50–90% at steam temperatures between 270ºC and 320ºC (Karthikeyan and others, 2009).

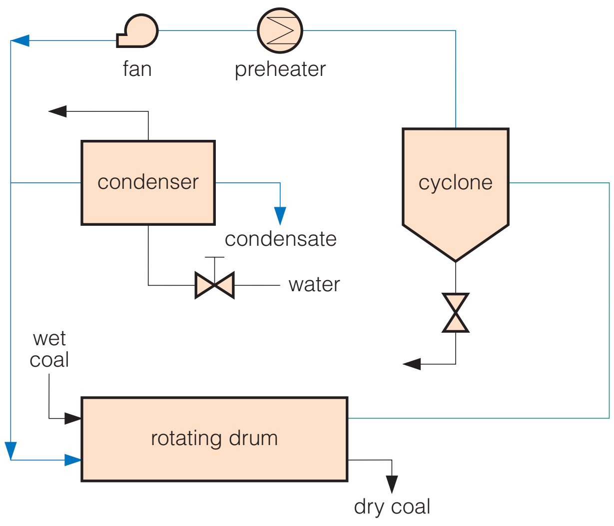


Figure 6 A schematic of Keith Engineering's superheated steam rotary dryer (Karthikeyan and others, 2009)

Because of the above mentioned advantages, SHSD is currently receiving increased interest for coal drying. One example is the WTA process discussed earlier. Another example is drying of lignite using Keith Engineering's SHSD process. Lignite from the Loy Yang lignite mine in Victoria, Australia, was tested using a superheated steam rotary dryer developed by Keith Engineering as shown in Figure 6. The average coal particle size was 8 mm. The feed rate of lignite was 23–46 kg/h and steam temperature was 180–230ºC with a drum rate of 3-6 rpm. Under these conditions, over 80% water removal was achieved and the moisture content of the lignite was reduced from 61% to 11%. Feed rate and inlet steam temperature were found to be significant parameters governing the process. SHSD was used for drying of Indonesian coal of relatively low moisture content that was rich in sulphur. A steam temperature of 300ºC was found to be sufficient to remove the moisture to the expected level (Jaugam and others, 2011).

3.1.5 Coldry Process

Developed by Environmental Clean Technologies Ltd (ECT), Australia, the Coldry process is a coal upgrading technology that removes high moisture content and certain pollutants from lignite and subbituminous coals, hardens and densifies the coal, and increases the heating value of low grade coal to more than 24 MJ/kg. These transform the coal into a stable, exportable black coal equivalent product for use by black coal fired power generators. A unique feature of the process is attritioning and extruding where the water is expelled from coal via an exothermic chemical reaction. The drying takes place under low temperature and low pressure so low grade waste heat from a neighbouring power plant can be used to facilitate the drying. The flow sheet of the Coldry process is shown in Figure 7. Lignite with moisture content between 30% and 70% is milled to particle size <8 mm in diameter and fed into a storage hopper (surge bin) where foreign objects are removed by screening. A small quantity of water (up to 5% depending on the moisture content of the raw lignite) is then added, and the coal/water mixture is fed into an attritioner in which the coal particles are rubbed together. This initiates an exothermic chemical reaction that triggers a natural process for expelling water from the coal. The reaction accelerates when the now plasticised mixture is extruded under low pressure. The extruded mixture is then sent to the conditioning unit in which warm air of around 40ºC heats the mixture for about an hour. At this point, the extruded product hardens, contracts and separates into pellets. The pellets formed are conveyed to a vertical packed bed dryer. Warm air from an adjacent power plant is circulated through the dryer to remove moisture from the pellets. The final moisture content of the product ranges between 10% and 14% depending on the water content and characteristics of the raw lignite, the drying temperature and drying time. The highly saturated warm air exiting the dryer at around 30ºC is cooled causing the water vapour to condense. The water is collected and may be used in a neighbouring power plant or for other commercial purposes.

ECT claims that the Coldry system is reliable and easy to maintain. It operates at low temperature and low pressure and thereby reduces energy consumption and extends equipment life. The Coldry pellets can be burnt for power generation but also provide an ideal feedstock for coal-to-liquid and coal gasification systems. A mixture of raw lignite and 10–30% Coldry pellets can be used in existing lignite-fired plants without modification to the plant, reducing CO_2 emissions by 5% to 15%. It is possible to fire 100% Coldry pellets in significantly upgraded lignite plants (http://www.ectltd.com.au/).

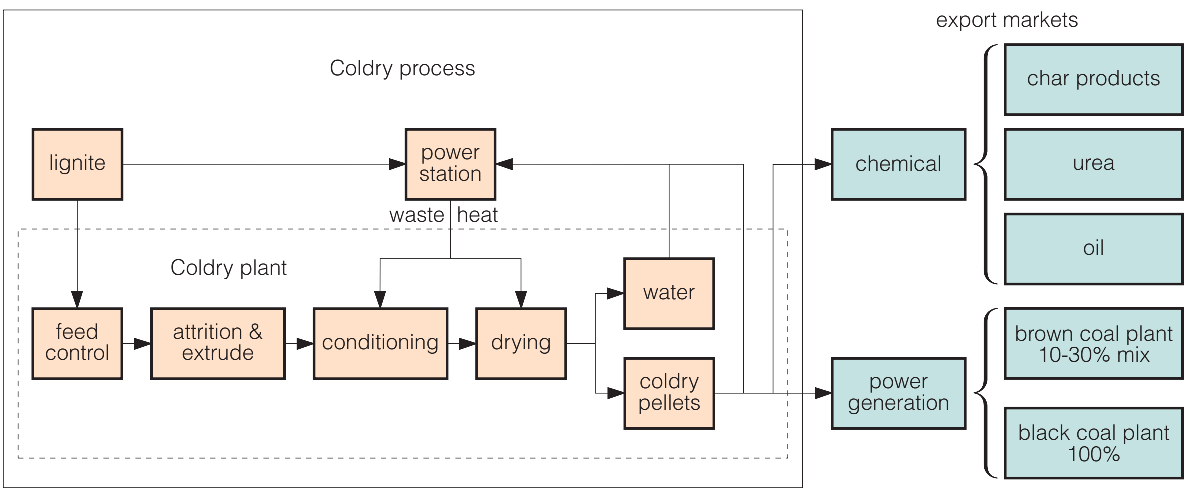


Figure 7 Coldry process (http://www.ectltd.com.au/wp-content/uploads/ColdryProcess21.jpg)

The Coldry Pilot Plant was established as a batch production facility in 2004. Further development during 2007 focused on the integration of its water recovery system and modifications to achieve continuous, steady-state production. In early 2011 a new mixer-extruder kit was installed and tested. The results showed that the new equipment could further increase production capacity while allowing ongoing refinement and calibration of the process for improved commercial scale design. The maximum production capacity of the plant is now around 20,000 t/y. It is currently run for testing and demonstration purposes, with some production sold into the local Victorian market to help offset some of the development cost.

3.1.6 Microwave drying

Microwave drying exploits the fact that water is super-absorbent to microwave energy. The water is heated at a molecular level, no matter where it occurs in the coal. Correspondingly, microwave energy can be efficiently delivered to both free and inherent water in the coal whilst the geological make-up of coal is largely transparent to microwave energy. By controlling the microwave energy applied and the residence time, water in coal can be removed effectively by vaporisation while the coal mass remains at low temperatures. This low temperature drying thus maintains the coal mass as intact as possible, preventing the deterioration of the coal's original thermal and other properties by overheating. However, the presence of impurities can result in hot spots, and high dielectric losses for coal can also result in fire hazards during drying. Further, it is difficult to comment on the cost involved for handling a large amount of coal (Jaugam and others, 2011).

Drycol® process

Under development by DBAGlobal Australia Pty Ltd through the Drycol® Project, the process involves exposing a continuous stream of coal to a controlled level of microwave energy to reduce its moisture content to a desired level. The moisture content of the product can be easily and precisely controlled through power setting and adjusting the conveyor speed. The microwaves have no particular heating effect on the coal, but efficiently target and drive off the water molecules situated on, around, or within it. The moisture is drawn off as a vapour, and may be condensed as a useful source of clean water. The basic concept of the Drycol® process is shown in Figure 8. The crushed raw coal is loaded onto a conveyor as a bed of fixed depth and conveyed continuously through a microwave-energised chamber for the moisture in coal to be removed. The coal temperature is maintained at or below 90ºC so that the processed coal neither devolatilises nor combusts. The process can be installed at a site remote to the power plant or at the existing power plant site. Also, the drying of coal can be performed during off-peak hours, minimising costs through load shedding (Graham, 2006).

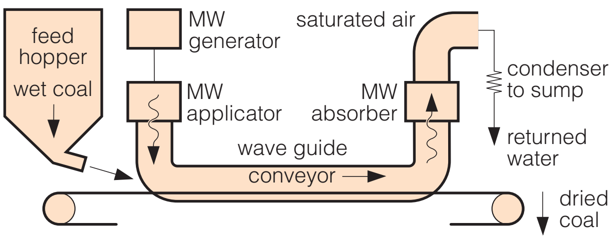


Figure 8 The Drycol® process (Graham, 2006)

A 15 t/h Drycol® plant was operated to commercially dry coal from 28% moisture content to 12% as replacement for coal destined for power generation. Tests on washed metallurgical coals showed that drying efficiency in the range 62–94% could be achieved using the Drycol® process (Graham, 2006). It was reported that microwave drying was much faster than the conventional coal drying. In some cases, it results in reduction of impurities such as sulphur, potassium, and phosphorous depending on coal type.

CoalTek Process

Developed and commercialised by a Georgia-based company, CoalTek Inc, this is a microwave-based process which removes moisture, ash, sulphur, and mercury from low rank coals and transforms them into cleaner burning fuels with an energy content increased by as much as 50%. This low temperature process is applicable to both thermal and metallurgical coal, and is capable of removing moisture while preserving the key metallurgical properties of coking coals. Typically, 40–50% moisture removal is achievable. It is claimed that all CoalTek by-products are captured, filtered and separated, meeting environmental standards. CoalTek has not revealed its technology so details of the process are unknown. CoalTek opened its first commercial processing facility in Calvert City, Kentucky, USA in 2006 and the plant's initial capacity of 120 kt/y will be expanded in the future (http://www.coaltek.com/). There are also plans to build additional CoalTek plants in China and USA.

3.1.7 High velocity air flow grinding/drying

This type of drying technology utilises high velocity and high pressure air to shatter coal particles so that moisture contained within the coal pore structures can be released. The sonic velocity air flow is so destructive that coal is instantly converted into a micron-sized fine powder with negligible moisture within. Since both the moisture content and particle size of coal decrease, drying and grinding can be achieved simultaneously, thus eliminating the difficulties attendant with grinding sticky low rank coals.

Windhexe technology

Developed by a US company Vortex Dehydration Technology, LLC (VDT), this technology is now commercially available for food processing and other industries. The Windhexe technology claims to be able to mill and dry coal simultaneously. The process showed the expected attribute of drying by evaporation but also produced a mechanical separation of moisture. The swirling air dehydrates the material using a combination of mechanical and evaporative energy and is therefore more efficient than any thermal drying device. The Windhexe device is described in a US patent as a cyclone with inlet tangential velocities equal to or approaching sonic velocity. The high velocity is achieved by the use of compressed air which is usually heated prior to entering the cyclone. The claimed energy requirement to remove water from coal is significantly less than water evaporation. The mechanism for achieving this is unknown (Wibberley and others, 2006).

According to VDT, over 800 tests of various materials were carried out and some of the most successful were energy related, especially coal. The Windhexe technology has been tested by International Power at the Hazelwood power plant to dry Australian lignite coal.

DevourX mill

DevourX mill is a vortex-based machine that is under development by DevourX Plc (Malaysia). It grinds and dries coal simultaneously using aeroacoustics rather than mechanical force. Aeroacoustics is the science of acoustic noise generation caused by aerodynamic forces interacting with surfaces. Around 1034 MPa pressure is reached through a combination of air speed and sound. The particles are accelerated from 0 to 100 km/h in 1 m of travel. Tuning of the machine is critical because the sound frequencies shatter the particles, followed by communition as the particles collide. Coal cells are 'pulled' apart and water is 'ripped' off from the coal particle converting clumpy wet lignite into a fine flowable powder that is carried in the air flow into the furnace (Godfrey, 2010).

DevourX claims that the system brings a number of economic benefits such as its high efficiency leading to reductions in processing costs and energy consumption, and a much smaller space is required for installation and less maintenance is needed during operation resulting in significant savings in capital and operational costs. Another advantage DevourX has over conventional drying is that it breaks the cellular structure of coal which liberates the colloidal moisture contained within the cells. Drying is achieved without the use of heat. However, the drying efficiency of DevourX can be enhanced by utilising the waste heat produced in a power plant.

LamiFlo™ system

Developed by a UK-based company LF Pumping (Europe) Ltd, the LamiFlo™ system is an integrated electricity-driven process that can be used for drying, transporting and grading more than 80 different materials including anthracite, bituminous and lignite coals. The system consists of three bespoke components connected with coated steel flanged pipework: mass air generators, the Anudro™ expansion chamber and the Euroclydon™ cyclone. The typical layout of a LamiFlo™ system is shown in Figure 9. A rotating Archimedes screw feeder feeds a moist feedstock into the Anudro™ expansion chamber where the solid is mixed with compressed air supplied by the mass air generator. The mixture then travels along the delivery pipe at high velocity up to 3000 m/min into a sealed Euroclydon™ cyclone, where the aggregates are separated from the saturated air stream. During the travelling, the air envelopes the moist solids and evaporates the surface moisture. The delivery pipe, typically 6 m long, can vary in length to suit the available space at a site. The process takes up to 3 seconds for moist material to enter the system and dried material to exit. Up to 10% surface moisture content can be removed per pass through the system. The drying takes place in air at low pressure but very high mass flow and no heat is used.

The LamiFlo™ drying system at low pressure removes free surface moisture. To reduce inherent moisture, the pressure within the LamiFlo™ system can be increased which increases the temperature of the air stream, resulting in inherent moisture reduction. In addition, particle reduction equipment can be incorporated to increase the surface to volume ratio of material and thereby enhance the drying efficiency. The LamiFlo™ system has design simplicity, is reliable to operate and easy to maintain. If the surface moisture content of a coal is to be reduced from 40% to 15%, the estimated operating cost is 0.58 \$/t at an output rate of 250 t/h or 0.63 \$/t at an output rate of 500 t/h based on electricity cost of 0.10 \$/kWh (LF Pumping, 2011).

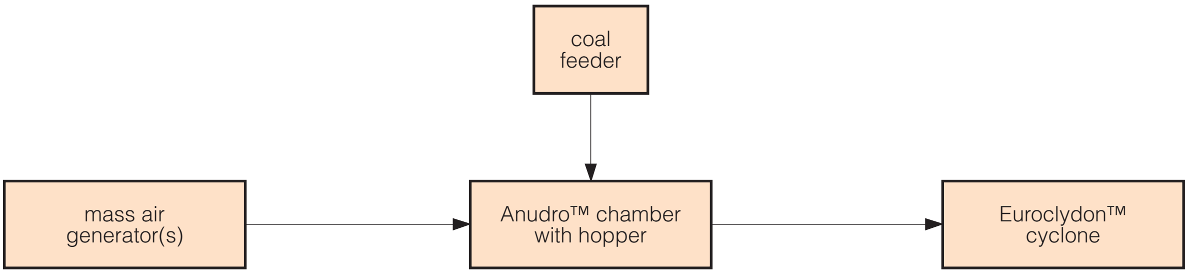


Figure 9 Typical layout of a LamiFlo™ system

3.2 Non-evaporative dewatering

The earliest non-evaporative thermal dewatering process was developed in Austria in the 1920s and is known as Fleissner drying. Since then a number of non-evaporative dewatering processes have been developed and technical reviews of these processes can be found elsewhere (Couch, 1990; Katalambula and Gupta, 2009). Hydrothermal dewatering and mechanical thermal expression are the two major types of non-evaporative coal dewatering. The following sections discuss some of the newer processes that are under development.

3.2.1 Hydrothermal dewatering (HTD)

In this process the coal is heated under pressure to temperatures in the range 250ºC to 310ºC. Under these conditions, the coal structure breaks down and shrinks, and the water is released as a liquid. Several hydrothermal dewatering processes are in development and are emerging in the commercial market.

K-Fuel®

Developed by Evergreen Energy Inc, a Colorado-based US company, K-Fuel® is a patented technology for low rank coal drying and upgrading. The K-Fuel® process involves the heating and

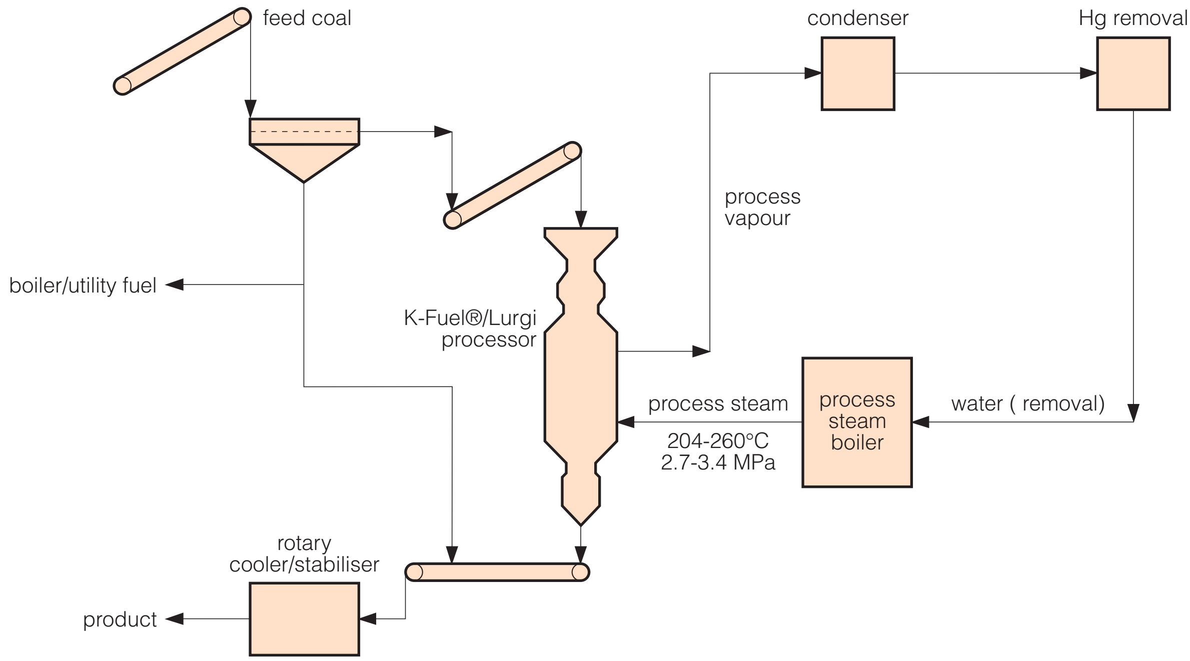


Figure 10 Flowsheet of the K-Fuel® process (www.evgenergy.com)

Table 5 Quality improvements in K-Fuel® products (Burton, 2011)

Coal	Moisture %			Higher heating value, MJ/Kg			Hg removal* %
	raw coal	dried coal	removal %	raw coal	dried coal	increase %	
Source 1	31.72	14.00	55.9	16.42	21.11	28.6	51
Source 2	44.96	14.80	67.1	14.92	23.72	59.0	68
Source 3	64.12	22.00	65.7	9.33	21.22	127.4	95
Source 4	51.91	24.60	52.6	13.15	21.52	63.6	54
Source 5	50.06	14.30	71.4	13.41	23.65	76.4	79
Source 6	26.95	13.20	50.0	20.05	24.54	22.4	43

* based on mass per unit of energy

pressurisation of low value coals, which irreversibly removes the water content thereby converting the product into a higher energy, lower emission fuel. The flowsheet of the K-Fuel® process is shown in Figure 10. In the K-Fuel® process, a low rank coal is fed into the K-Fuel® processor. High temperature (204–260ºC) and pressure (2.7–3.4 MPa) are applied in the processor to crush the coal and under such harsh conditions, the physical and chemical structure of the low rank coal is altered transforming the low rank coal into a cleaner, low-moisture and higher-CV fuel. A co-benefit of the K-Fuel® process is that it can also remove significant amounts of mercury (as much as 80%) and lower impurities present in the coal and thereby reduce overall emissions of SOx, NOx, CO_2 and Hg from coal-fired power plants.

A 750,000 t/y commercial K-Fuel® plant was built in Gillette, Wyoming, USA and operation, modification and test burns were carried out from December 2005. Based on the operating experiences obtained at the plant, the K-Fuel® process was redesigned in 2008 by Bechtel Power Corporation. This enhanced K-Fue® process design offers significant process, economic, and environmental improvements and it is now the template for Evergreen's business development activities in the USA and abroad (Burton, 2011; Katalambula and Gupta, 2009).

A number of lignites and subbituminous coals including coals from Inner Mongolia, Indonesia, Russia and the USA were tested and examples of the improvements in coal quality achieved by K- Fuel® process are shown in Table 5. As one can see from Table 5, the K-Fuel® process is capable of reducing moisture content of low rank coals by more than 50%. The heating value of the coals was increased as a result , and in one incident the high heating value of a coal was more than doubled after drying. In addition, the mercury content of coals can be effectively removed by the K-Fuel® process resulting in a significant reduction in Hg emissions from power plants. The K-Fuel® treated coals were test burned in several US power generation facilities and the results confirmed the improved combustion efficiency and reduced air emissions. Evergreen Energy is now actively working to commercially deploy this technology globally. In 2010, Evergreen Energy reached an agreement with a Chinese company to establish a joint venture, which signed a letter of intent with a large Chinese utility and chemical producer to explore ways in which the K-Fuel® technology could be applied at an inland coal chemical facility that was under development. In 2011, Evergreen Energy signed agreements with an Australian mining company WPG Resources to set up a joint venture to develop and deploy the K-Fuel® technology throughout Australia (www.evgenergy.com).

Continuous Hydrothermal Dewatering (CHTD)

An Australian company, Exergen, has developed CHTD which been successfully demonstrated at pilot scale on coals from Australia and other international locations. Core to the CHTD technology is a vertical autoclave that uses gravitational head pressure and a small amount of energy to transform the molecular structure of lignite/brown coal to remove up to 80% of its moisture content. The use of gravitational pressure and high heat recovery design means that less than 2% of the coal's energy is used to achieve greater than 60% reduction in water content for Victorian lignites. A schematic process flow of CHTD is shown in Figure 11.

The process utilises efficient heat and pressure recovery to achieve the decarboxylation of lignite/brown coal. Heat recovery is greater than 90% due to efficient autoclave design. The process exerts 10 MPa and 300ºC upon a brown coal slurry for a period of a few minutes. These conditions alter the molecular structure of the coal, collapsing pores within the coal particle and making it unable to hold as much moisture. The coal changes from being hydrophilic (water attracting) to hydrophobic (water repelling), allowing the water to be removed from the coal more easily. The chemical transformation of the coal reduces its ability to carry moisture, which lowers its equilibrium moisture content, making it less likely to absorb atmospheric moisture. The water is extracted from the coal in a liquid state, producing a coal with higher energy density. Furthermore, some impurities in the coal are removed in the CHTD process resulting in a coal with improved combustion characteristics. For example, soluble inorganics are separated from the coal with the water. Up to 60% of sodium is

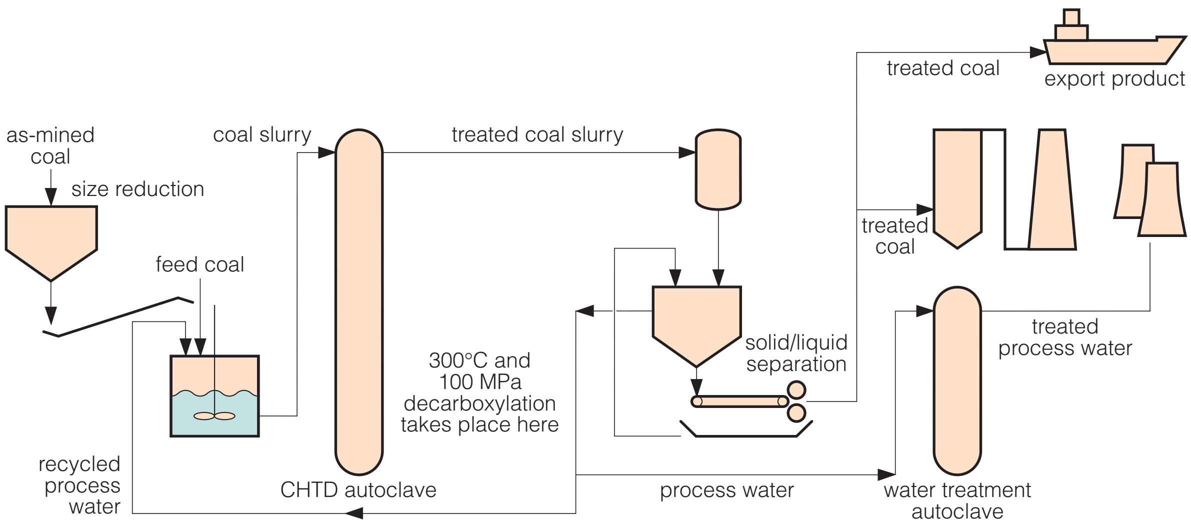


Figure 11 CHTD process (Exergen, 2009)

removed, reducing the power station maintenance costs associated with boiler slagging. Dense components of the ash (such as quartz) may be removed from the coal slurry, leading to reduced wear on power station equipment. As an additional benefit, the water extracted from the coal can meet up to 40% of the make-up requirement for power station cooling. Exergen claims that the CHTP process is simple, continuous with a small footprint and can be readily up-scaled to a feed rate of thousands of tonnes per hour (Exergen, 2009).

Having successfully proved the CHTD concept in its 4 t/h pilot plant, Exergen has been working on scaling up to a 50 t/h demonstration plant and after that Exergen plans to build a 4000 t/h commercial-scale facility adjacent to a new 30 Mt/y brown coal mine in Latrobe Valley (LV), Australia that is under development by Exergen to upgrade LV brown coal for export (www.exergen.com.au).

Hot Water Drying (HWD)

Developed by researchers at the Energy and Environmental Research Center (EERC) of the University of North Dakota, the HWD process uses high temperature and high pressure to dry a coal in a water medium. In the HWD process, ground wet coal is treated at coal-specific temperatures, beginning at as low as 240°C and the corresponding saturated steam pressure for less than ten minutes. Moisture is removed from the coal by expansion and expulsion from the micropores by CO_2, which is liberated during decarboxylation. Devolatilised tars/oils, which are hydrophobic, remain on the coal surface in the pressurised aqueous environment. It is hypothesised that this produces a uniform coating that seals the micropores and limits moisture reabsorption, which is a major advantage of the process. Because the coating retains most of the low-rank coal's volatile matter, high energy recovery and excellent combustion performance can be obtained. The developers claim that alkali cations, a major source of boiler fouling, associated with the carboxyl groups, are released in the aqueous phase in the process and are removed during the final mechanical dewatering step.

The technical feasibility of HWD has been demonstrated in a 7.5 t/d pilot plant at the EERC with low rank coals from around the world. Costs of dewatering will vary with coal grade and location. It appears that the successful commercial low rank coal drying processes are those in which the dried low rank coal is utilised immediately and not stored. When stored, the products from most drying systems can have stability problems, which result in excessive fine dust and spontaneous heating (Karthikeyan and others, 2009).

The Catalytic Hydrothermal Reactor Technology (Cat-HTR)

An Australian company Ignite Energy Resources Pty Ltd (IER), is developing the catalytic hydrothermal reactor technology which is designed to convert low value lignite and modern biomass into non-conventional crude oil and various upgraded coal products. The Cat-HTR technology uses water at or near supercritical temperatures and pressures together with proprietary catalyst systems to selectively de-polymerise and de-oxygenate lignite and convert it into various higher density energy fuels and high grade clean coal products. A diagram of Cat-HTR process is shown in Figure 12. The company has not disclosed much factual information so details of the technology remain uncertain.

A pilot scale Cat-HTR plant with capacity of 4000 t/y has been in operation since mid-2008. Based on the pilot test results IER claims that Cat-HTR has the capability to convert 1.3 t of as-mined lignite (assuming 50% moisture) into up to one barrel of non-conventional crude oil and up to 0.34 t of high grade micronised coal.

In 2010, IER signed a hosting agreement with TRUenergy, a Victorian-based utility company and subsidiary of China Light & Power, to build a commercial Cat-HTR demonstration plant at TRUenergy's site at Yallourn and to supply upgraded fuel products to TRUenergy's existing lignite-fired power station (http://www.igniteer.com/).

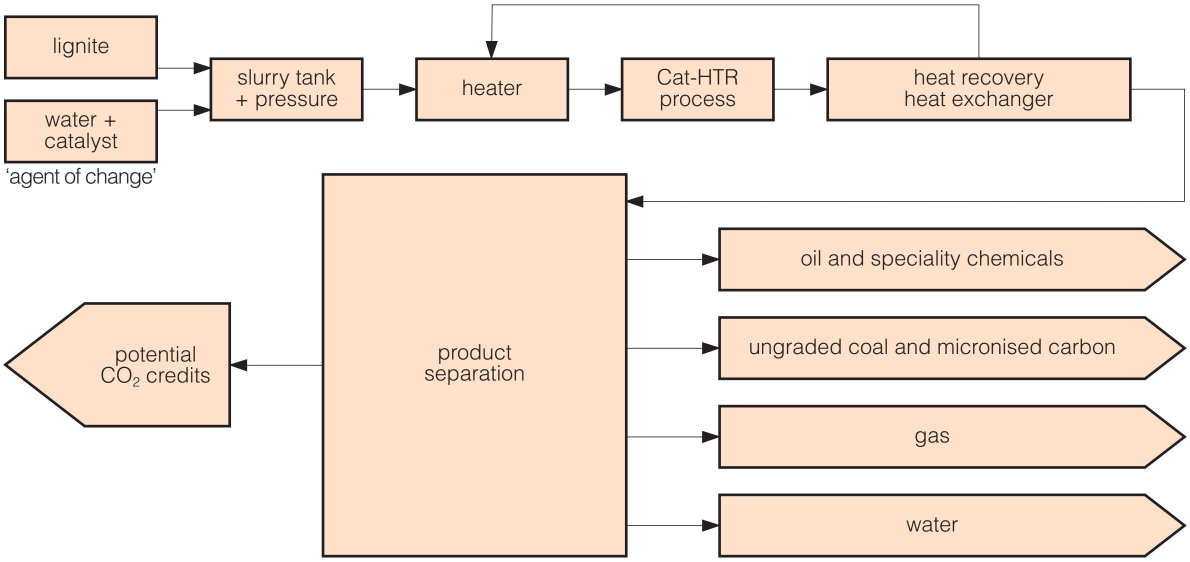


Figure 12 Cat-HTR process diagram
(http://www.igniteer.com/technology/lignite-upgrading/cat-htr-process.html)

3.2.2 Mechanical thermal expression (MTE)

Studies undertaken by Professor Strauss and co-workers at the University of Dortmund, Germany in the mid 1990s led to the development of MTE technology that combines the use of pressure and temperature to effectively reduce the moisture content of lignite, while requiring significantly lower pressures (<12 MPa) and temperatures (<200ºC). The effect of elevated temperature is to soften the coal to reduce the mechanical pressure required for dewatering. In the MTE process, raw lignite is heated to a temperature in the range of 150ºC to 200ºC, at saturation pressure (0.5 to 2 MPa) to prevent evaporation. A mechanical pressure of around 6 MPa is then applied to squeeze the water out of the lignite. A schematic of MTE process design is shown in Figure 13.

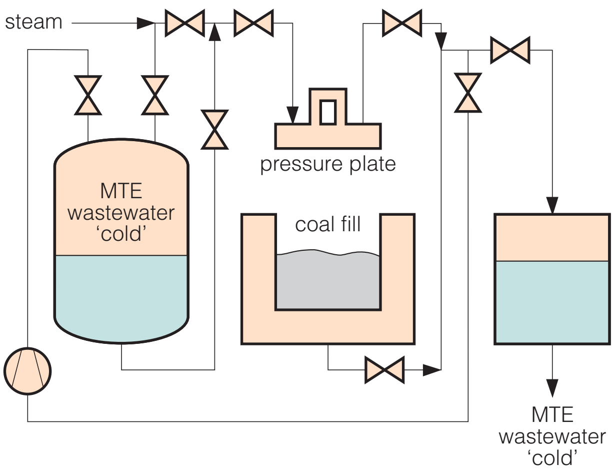


Figure 13 MTE process design (Wibberley and others, 2006)

There has been active development of this technology in both Germany and Australia. In Germany, the development of the MTE technology has been undertaken by RWE in collaboration with other companies. Following successful trials at laboratory- and pilot-scale using batch process, a further development step toward commercial implementation of the MTE process involved converting the discontinuous pilot press to quasi-continuous fully automatic operations, with a throughput of approximately 1.6 t/h of dried lignite. While testing the MTE technology, the feeding of the MTE press with coal in quasi-continuous operations, treatment of the raw lignite, and subsequent treatment of the dry lignite produced were also investigated. The various project phases provided evidence of the cost-effectiveness and energy-efficiency of dewatering lignite using the MTE process. After completion of this development, a 25 t/h MTE demonstration plant was constructed at RWE's Niederaussem power plant and was commissioned at the end of 2001. At the beginning of 2002 RWE took over the demonstration plant but work was subsequently discontinued. RWE has chosen the WTA process for further development (Katalambula and Gupta, 2009; Bergins, 2005).

In Australia, the Cooperative Research Centre for Clean Power from Lignite (CRC Lignite) worked to develop the MTE process suitable for Victorian lignites. The development plan involved the construction of a 20 t/h pilot plant in 2005 to 2006. The CRC's MTE process used a different configuration that had some features distinctly different from those of the German process. In the CRC's process, the coal was fed as a slurry, which was preheated using energy extracted from the hot product coal and hot expressed water. The preheated coal slurry was then heated under pressure in a heating chamber to the required process temperature by saturated steam. The hot slurry from the heating chamber directly entered the compression cylinder under gravity. Dewatering occurred through both axial and circumferential filter surfaces. The circumferential filter surface, a feature of the CRC's process, appeared to be more effective in dewatering than the axial surfaces. This improvement meant that the dewatering in the CRC's process was not as dependent on particle size distribution as was in the German process.

The CRC Lignite reported on the successful trial of the CRC's MTE process for drying lignite and concluded that this technology could provide a low cost, energy efficient process for partial drying (down to around 30% moisture) at the large scale required for power plant feed. The CRC Lignite found the MTE less expensive than HTD or WTA process and capable of removing more than 70% of the water from the lignite from Victoria and South Australia, resulting in huge CO_2 savings when the dry coal is burnt in a power station (Katalambula and Gupta, 2009; Wibberley and others, 2006).

The liquid water removed from coal by HTD and MET processes carries with it both organic and inorganic mater. The large volumes of acidic, salty, and organic-rich product water present a major concern of wastewater treatment difficulties and costs for disposal or reuse of the product waters. The overall viability of the processes will depend on the availability of a simple and energy-efficient water remediation strategy. Investigations into ways of treating the wastewater from HTD and MET processes were carried out by several researchers (Nakagawa and colleagues, 2004; Butler and others, 2007) and more work in this area is needed.

3.2.3 Comments

When selecting a lignite drying process for power plant applications, factors such as throughput, energy consumption, material handling capabilities, safety, carbon footprint, capital and operating costs are important considerations. Although numerous technologies for coal drying already exist, not all are suitable for lignite drying and often they are complex and require high-grade heat to remove moisture from the coal. This significantly increases process cost, which represents a main barrier to industry acceptance of the technology.

Extensive research and investigations have been carried out worldwide to develop energy efficient and cost effective coal drying processes. A number of approaches are taken to dry lignite and other low rank coals. The variability and diverse nature of lignite properties make testing at pilot scale imperative in the development of new drying technologies. Furthermore, there is a need for careful and systematic evaluation of dryer designs to maximise the efficiency, cost-effectiveness, and safety of drying equipment selected for a specific lignite application. Recently, several advanced coal drying technologies have been developed and are offered to the commercial market, whilst many more are under development. A comprehensive review on the recent developments in drying of low rank coal is available (Osman and others, 2011). This is an area that is developing rapidly.

4 Pulverised lignite firing

The major challenge facing the power generation industry over the coming decades will be to increase the efficiencies of fossil-fuelled power plants while also meeting more stringent environmental goals. Especially, 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. At the same time, plant reliability, availability, maintainability and operational costs, as well as the cost of electricity (COE), must not be compromised. Pulverised coal combustion (PCC) technology has continued to evolve over time from subcritical to supercritical (SC) and ultra-supercritical (USC) steam conditions leading to significant increases in unit efficiencies. In addition to the use of advanced steam cycles, technical innovations in system and process engineering, larger unit size, improved waste heat recovery from the flue gas, and optimisation of auxiliary power needs have all contributed to the plant efficiency increases and costs reduction. In the last ten years, significant improvements also have been achieved in reducing heat losses in the low-pressure end of steam turbines and in turbine blade designs, improving both efficiency and reliability of the overall generating units. As a result, today's PCC power plants have very high levels of availability and reliability. Furthermore, the continued addition/retrofit of emission control systems to meet progressively more stringent emission standards has resulted in significant reductions in air pollutants emissions. In lignite-fired power plants, flue gas desulphurisation (FGD) systems are applied for SO_2 emissions control while NOx emissions control is mainly accomplished by primary measures.

4.1 Pulverised lignite firing process

In a conventional pulverised lignite fired boiler, the lignite fuel is fed into bunkers adjacent to the boiler. From there, the fuel is metered into several pulverisers which grind it to approximately 200-mesh particle size. A stream of hot gas (flue gas drawn from the lower part of the boiler) is introduced into the mills to dry the fuel and to convey it pneumatically to the burner nozzle where it is injected into the burner zone of the boiler. Firing configurations of boilers that fire pulverised lignite include tangential, horizontally opposed, front wall, and cyclone boilers.

In the tangential firing furnace, the pulverised lignite is introduced from the corners or walls of the boiler in vertical rows of burner nozzles. Such a firing mechanism produces a vortexing flame pattern which essentially uses the entire furnace enclosure as a burner. In front-wall firing and horizontally opposed firing boilers, the pulverised lignite is introduced into the burner zone through a horizontal row of burners. This type of firing mechanism produces a more intense combustion pattern than the tangential design and has a slightly higher heat release rate in the burner zone itself.

In these methods of firing pulverised lignite, the ash is removed from the furnace both as fly ash and bottom ash. The bottom of the furnace is often characterised as either wet or dry, depending on whether the ash is removed as a liquid slag or as a solid. PCC units have been designed for both wet and dry bottoms, but for lignite firing the current practice is to design only dry bottom furnaces.

Another type of boiler firing lignite is the cyclone boiler, which is a slag-lined high-temperature vortex combustor. The coal is fed to a crusher that reduces the lignite into particles of approximately 0.6 cm (0.25 inch) in diameter or less. Crushed lignite is partially dried in the crusher and is then fired in a tangential or vortex pattern into the cyclone boiler. The temperature within the furnace is hot enough to melt the ash to form a slag. Centrifugal force from the vortex flow forces the melted slag to the outside of the combustion zone where it coats the boiler walls with a thin layer of slag. As the solid lignite particles are fed into the boiler, they are forced to the outside of the combustion zone and are embedded in the slag layer. The solid lignite particles are trapped there until complete burn-out is attained. The ash from the furnace is continuously removed through a slag tap which is flush with the furnace floor (US EPA, 1998). There are only a few lignite-fired power plants in operation using cyclone boilers.

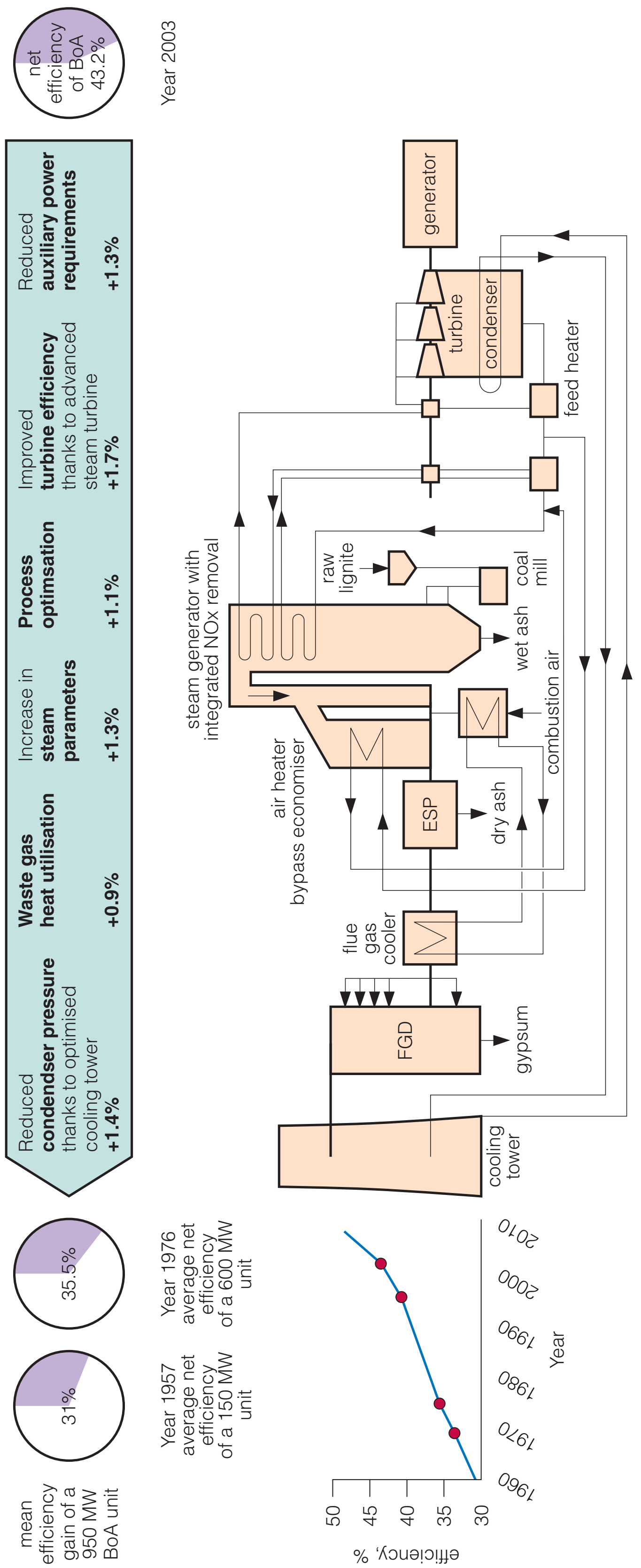


Figure 14 Efficiency gains of a RWE's BoA unit from improvements in lignite-fired power plant process and engineering design (RWE Power, 2011)

Most lignite-fired power plants around the world in operation today use PCC technology. The majority of existing pulverised lignite fired power plants are based on the conventional single reheat thermal cycle with subcritical main steam pressure in the range 13–20 MPa and main/reheat steam temperatures both around 540ºC. There are some old, small, lignite-fired generating units that are still in operation with main steam pressure at or under 10 MPa and some of them have main steam temperatures well below 500ºC (IEA CCC, 2011).

Recent advances in boiler and turbine materials have led to the installations of high efficiency supercritical and ultra-supercritical PCC steam generators. In modern lignite-fired power plants, steam pressures up to 27.5 MPa and main/reheat steam temperatures as high as 600ºC/605ºC have been applied, and the net plant efficiency of >43% has been achieved. Improvements in process design and engineering not only increased the total plant efficiencies, but also improved the availability, flexibility and environmental performances of the plants and reduced capital and operating costs. Technical advances in system and process engineering include (Mandel and Schettler, 2007; Wolff, 2011):

- improved low NOx burners;
- an optimised heat cycle for the regenerative preheat unit;
- the reduction of condenser pressure;
- improved recovery and utilisation of waste heat from the flue gas;
- the use of efficiency-improved bladings at the steam turbines;
- increased use of fibre-glass reinforced plastics and flue gas draw off through the cooling tower;
- the introduction of highly efficient after-burning grates with residues of lower than 1% of unburnt material;
- combustion chamber cleaning with the help of water jet sprayers.

Figure 14 shows the efficiency gains of RWE's 950 MWe BoA unit from improvements in lignite-fired power plant process and engineering design. BoA is the abbreviation of 'the lignite-fired power station with optimised plant engineering' in German. With BoA Plus, which is BoA technology plus WTA lignite pre-drying technology, the plant efficiency can be further increased by up to four percentage points. Some of the new design concepts for pulverised lignite fired power plants will be reviewed in the following sections.

4.2 Lignite milling

The milling plant for lignites is fundamentally different to the mills for bituminous/hard coals. The key issue for pulverising lignites is to achieve adequate drying and to avoid mill fires. This is achieved using flue gas in addition to air for drying and this gives the heat required and also reduces the oxygen concentration in the mills to a level where explosions cannot occur. Due to the soft nature of lignite coal, beater wheel mills are normally used to pulverise the lignite to achieve defined fineness and to lower its moisture content to the desired level to ensure efficient combustion of the fuel. A beater wheel mill crushes, shatters, or pulverises lignite upon impact. The fineness of pulverised coal is usually assessed on the basis of the residues on the 1 mm sieve. The typical values for pulverised lignite are well below 10% (usually between 3% and 6%), depending on quality of coal, the combustion system and boiler size.

In order to provide pulverised lignite with the required fineness, moisture content and fuel flow rate, several modifications and improvements on the existing beater wheel mills were implemented and tested. Various types of beater wheel mills are shown in Figure 15.

4.2.1 Beater wheel mill with classifier

The lignite processing takes place in the mills without staged grinding. The mills are equipped with classifiers. These classifiers are static separators with no moving parts. The use of the classifiers ensures that the residue on the 1 mm sieve does not exceed 3% to 5%. The fraction of <63 µm is equivalent to about 70–90%.

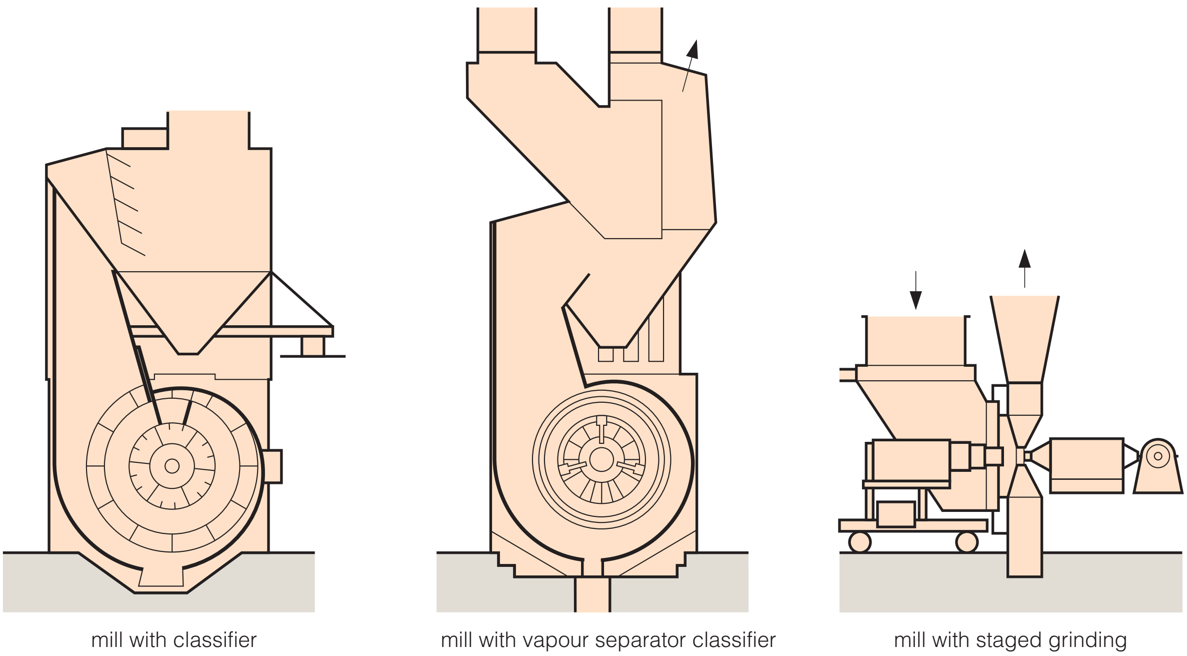


Figure 15 Types of beater wheel mills (VGB, nd)

These devices employ gravity deflection to separate the coarse dust fractions from fuel dust/gas mixture and return the coarse grains to the mill for further grinding. These classifiers cannot meet the increasing demands of modern large lignite-firing plants – in particular the flame stability at varying boiler load because the low O_2 content of carrier gas and high moisture content of the fuel have a negative effect on coal ignition and combustion efficiency.

4.2.2 Beater wheel mill with vapour separation classifier

This is an improved version of the mills discussed above through the use of vapour separation classifiers. The vapour separation classifier performs two tasks: it separates the coarse grains from the fuel dust/gas mixture and returns them to mill for further processing, and it splits the mixture into fuel-rich and fuel-lean vapour streams. The split streams are then fed to the combustion chamber separately. The degree of vapour separation can be set, for example, 90% fuel dust and 70% gas in the fuel-rich stream, and 10% fuel dust and 30% gas in the fuel-lean stream. The fuel-rich stream is injected into the boiler through lower main burners and the fuel-lean vapour stream is injected through the remaining upper part burners or through additional vapour burners above the main burners.

4.2.3 Beater wheel mill with staged grinding

For some lignites with high hardness and poor grindability, beater wheel mills with staged pulverising/grinding can be used to achieve the required fineness. The mills are designed without classifiers. The grinding of the mills is subject to greater fluctuations due to the lack of classifiers and the residue on the 1 mm sieve is, on average, 6–9%.

Mills with classifiers/vapour separation classifiers and with staged grinding are also available, which combine the features discussed above.

The mill design for the RWE's BoA 2 and 3 at Neurath Power Plant (Germany) features a three-stage prebeater and a beater wheel with a diameter of 4.3 m. The two-stage grinding process ensures the required product fineness of <6–10% residue on 1 mm sieve being maintained independent from load or lignite quality (Habermann and others, 2004).

The number of mills in operation depends on calorific value at nominal load. Apart from the number of mills in operation the mill conveying volume is adapted to the coal quality by the means of mill speed control and conveying gas recirculation. The mills are arranged symmetrically around the furnace and they feed dried and finely-ground lignite directly to the corresponding burner columns.

In general, for lignite/brown coal combustion there are no special demands on the fineness of the pulverised fuel in order for primary NOx emissions control. However, finer fuel particles may reduce deposition and slagging problems.

4.3 Low NOx burners

The design of a furnace is strongly governed by the burners to be installed. Their arrangement and performance determine the size and shape of the furnace. The burner performance also influences the mill design to a certain extent. Therefore, the burner is the key element in the design of a firing system.

Most existing lignite-fired units in Europe use tangential firing system with jet burners, where the flame is stabilised in the central fireball instead of individual vortex burners. These jet burners are actually not burners but coal injectors which means that lignite coal ignites 2–4 m from the nozzle in

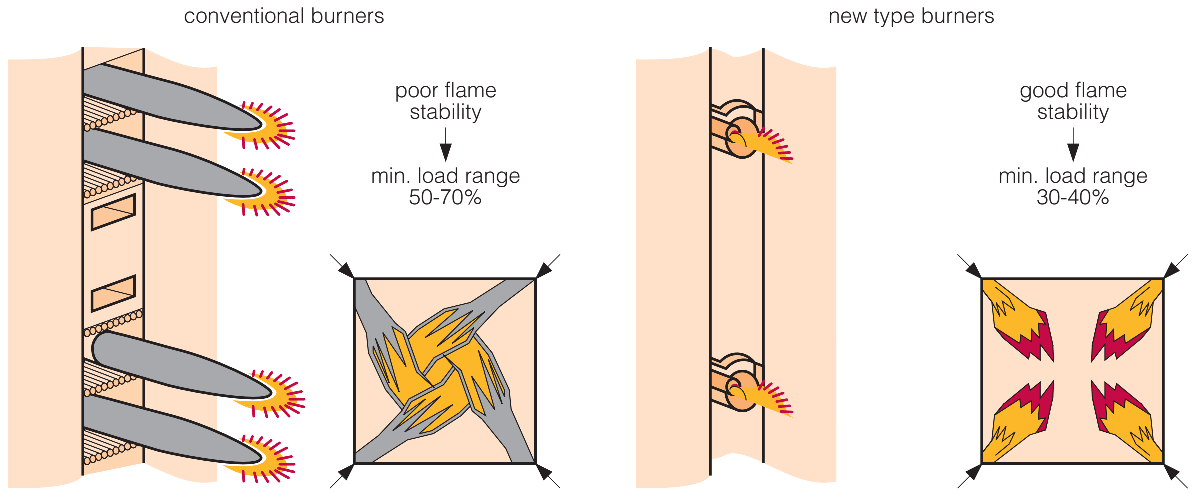


Figure 16 The new lignite combustion system with NR-LE burners (Yano and others, 2003)

the central fireball. Due to the low O_2 content of the carrier gas, the ignition and flame stabilisation are inferior with such a jet burner. This results in a narrow operating range for boilers, typically 50–100 % and under low load operation it is necessary to use oil or gas for flame stabilisation and for safe boiler operation. These burners also result in high NOx emissions and suffer slagging problems.

Babcock-Hitachi and Enprima Engineering developed a new type of low NOx burner called NR-LE (NOx Reduction – Load Extension) burners for lignite combustion that apply the 'high temperature' philosophy. The basic feature of a firing system using the NR-LE burners is that a sub-stoichiometric zone is formed very close to the burner nozzle, and two-stage combustion is carried out by means of a single burner flame. This single burner staging technique combined with staging in the main vortex by OFA (over fire air) is very effective in reducing NOx emissions (Yano and others, 2003).

In order to reduce slagging in lignite fired units, sometimes it is necessary to increase the vertical distance between burner levels to reduce the burner zone heat release rate related to temperature in the burner zone, and to modify the corner geometry so that flame impingement on the furnace wall is prevented. Figure 16 shows the principle of the new combustion system with the NR-LE burners. Furthermore, the NR-LE burner can control the flame pattern making it possible to avoid the high temperature influence on slagging to furnace corner walls.

The NR-LE burner found its first commercial application in Unit 2 at Vresová lignite-fired power plant in Czech Republic in 2001. Results showed that after retrofitting NR-LE burners and modifications to the OFA system, NOx emissions were reduced to lower than 200 mg/m^3. The boiler turndown ratio has been improved and stable operation within the full load range (30–100%) can be maintained (Yano and others, 2003).

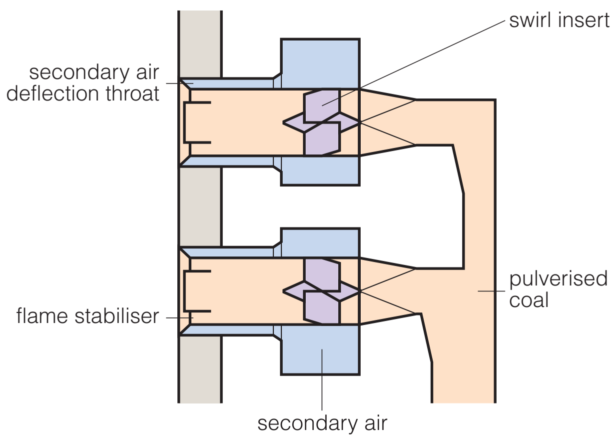


Figure 17 RS burner for lignite combustion (Tigges, 2003)

With the use of CFD (computational fluid dynamics) modelling, Babcock Borsig Power Systems (Germany) developed the RS burner for lignite combustion as shown in Figure 17. RS burners are characterised by stable flames with ignition right at the burner tip. This leads to a higher heat absorption in the lower part of the furnace. In 2000, the RS burners were retrofitted to the 300 MWe units A and B at

Neurath Power Station (Germany), which burns lignites of different qualities from two mines, Hambach and Garzweiler. The RS burners were installed in the burner opening of the former jet burners and similar to the jet burners, they are directed towards a tangential circle in the furnace. Only slight adjustments were made to the boiler pressure parts. The excellent low NOx performance of the burners resulted in reduced OFA requirement and therefore the uppermost of three OFA elevations situated between the first tube banks could be removed without any increase in NOx emissions. The particle temperature at the furnace exit was 50°C to 70°C lower after the conversion and consequently the severe slagging and fouling at the furnace exit and first tube banks experienced previously were substantially reduced. Stable full load conditions and complete burn-out at the furnace exit were also achieved. Furthermore, with RS burners, higher burner air ratios and shorter residence times of fuel combustion in reducing atmospheres are sufficient to meet the NOx emission requirements compared to jet burners (Tigges, 2003).

4.4 Boiler design

4.4.1 Firing system

Lignite firing systems for utility boilers are mostly designed as tangential firing systems with main and reburning burners. The fuel is fed into the combustion chamber symmetrically. One mill feeds one burner group. The uniform fuel supply to the furnace cross-section generates an optimum temperature profile with hot zones in the centre of the furnace cross-section and colder zones at the edge. Symmetrical firing configuration allows uniform heat flux and temperature distributions in the burner area which will reduce slagging. The burners are arranged in the corners to maximise the utilisation of the furnace volume and minimise the back-flow zones at individual burner. As a result, smaller amounts of hot flue gases containing unburnt coal particles reach the combustion chamber wall, which would otherwise cause fouling of the chamber wall. The pronounced radial temperature profile is produced by directing part of the secondary air towards the walls. This results in more combustion air in the wall area which leads to lower temperatures in the peripheral area which reduces the propensity for fouling.

Figure 18 shows an overview of the firing concept. It includes a combustion chamber for a 1050 MWe steam generator. The burner array of the combustion chamber corner consists of six dry lignite fired burners arranged one on top of the other. Each of these burners has been allocated a wall air opening. These fuel oil burners centred within the dry lignite burner and equipped with a swirl are used for ignition firing.

This firing configuration with radial-staged air supply represents the state-of-the-art for modern hard coal based firing systems. In addition to this type of air supply, two burn-out air levels are planned. This staged air supply concept guarantees compliance with the statutory emission values for NOx and CO. In pulverised lignite fired plants of lower capacities, the limits were almost always achieved. Furthermore, co-combustion tests with dry lignite in conventionally-fired plants showed that this operating mode did not cause any rise in NOx emissions. In industrial-scale plants with long residence times and efficient staged air supply, the EU emission limit values are therefore reliably achieved (Ewers and others, 2003; RWE Power International, 2006).

For lignite-fired boilers without fuel pre-drying plant, the high moisture content of lignite necessitates the use of recirculated flue gas at high temperatures (approximately 1000°C) from the furnace exit to dry the lignite to a residual moisture content of around 20%.

The lignite is burnt at temperatures of around 1200°C. The hot flue gas that emerges during combustion flows upwards through the steam generator transferring heat to the outer walls formed by tubes and to the tube banks suspended in the flue-gas flow. Heated feedwater flows through these tubes and is evaporated and superheated.

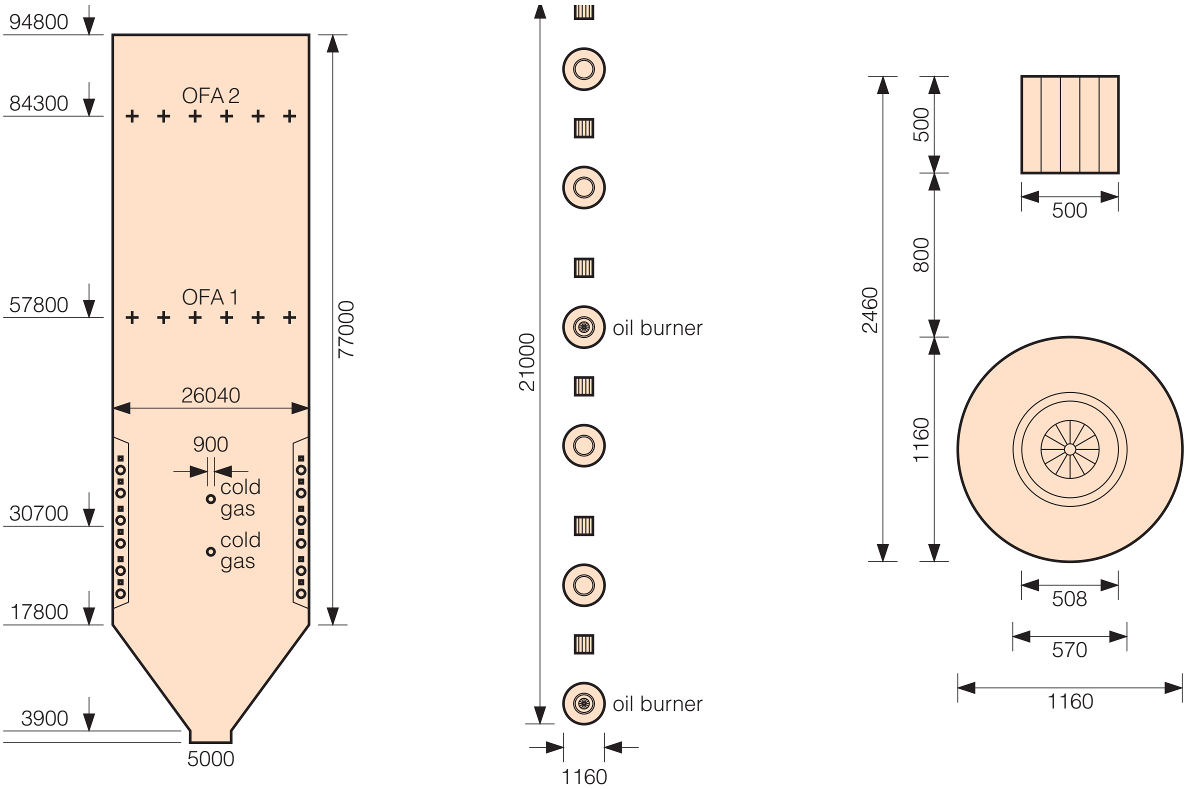


Figure 18 Firing concept for an utility-scale, dry lignite-fired boiler (Ewers and others, 2003)

Beyond the topmost bank of heating surfaces, the flue gas is directed downwards through the open-pass duct across the flue-gas air heater. After flowing through these heat exchangers, the flue gases, cooled to approximately 160°C, are ducted to the flue gas cleaning systems for dust collection and desulphurisation (RWE Power International, 2006).

4.4.2 Boiler size

A key issue for supercritical boiler design is the furnace exit gas temperature (FEGT). In order to avoid severe deposition in the convective heat transfer part of the boiler it is necessary to ensure ash particles are not still molten at this point. In general, the design FEGT is at least 50°C lower than the lowest value expected for the IDT (initial deformation temperature) for the coal range under consideration. Typical values for FEGT for boilers burning hard coals are in the range 1150–1200°C. For lignite burning plants, the FEGT is typically 150–200ºC less than this. The net result is that lignite boilers need to be taller and have a much greater cross-section than boilers for hard coals (RWE Power International, 2006).

The modern large lignite boilers that are in operation use furnace dimensions of up to 24 x 24 m and furnace heights of up to 84 m. The world's largest lignite-fired boilers, which are being commissioned now, are the RWE's 1100 MWe BoA 2 and 3 with furnace dimensions of 26 x 26 m in cross-section and 87 m in height. The boiler height is 142 m. The larger furnace cross-section can help to reduce furnace height and result in a moderate cross-sectional area heat release which in turn lowers the temperature level in the principal combustion zone. A three-dimensional CFD analysis was performed to validate those furnace dimensions. Overfire air penetration, CO burn-out and temperature patterns were the areas of concern. The results of the CFD analysis confirmed similar combustion performance to the BoA 1 already in operation (Habermann and others, 2004; Ewers and others, 2003; Elsen and Fleischmann, 2008).

4.4.3 Thermal design

In BoA technology, the once-through tower-type boiler, used as supercritical steam generator, can be designed for both modified and pure variable pressure operation with up to 45% load in recirculation mode and 45% to 100% load in once-through operation. Figure 19 shows the BoA 1 steam generator at Niederaussem Power station.

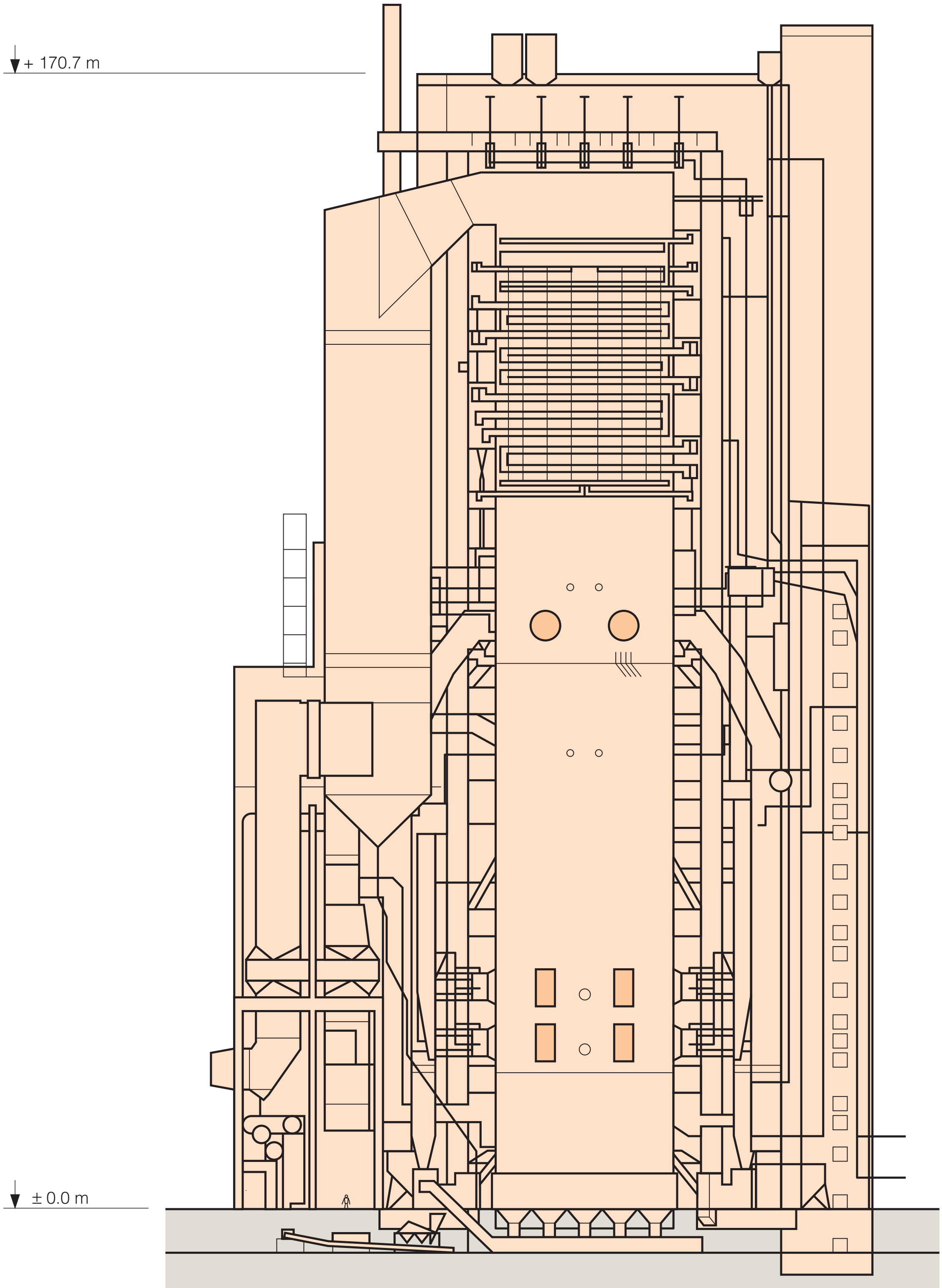


Figure 19 The BoA 1 steam generator at Niederauseem Power station (Habermann and others, 2004)

The main design parameters of a steam generator include the capacity, pressure and temperature of the main and reheat steam, FEGT, feedwater temperature, and the characteristics of the fuel. The coal properties, especially the slagging and sintering properties, have a major influence on the thermal design. The FEGT is determined by the IDT of the reference coal.

In the BoA technology, the circuit arrangement on the water steam side of the steam generator is as follows: first, the feedwater passes through the economiser. It then enters the helical-wound furnace hopper, from where it goes to the evaporator helix. Due to the high heat absorption in the combustion chamber and the limitation of the admissible medium temperature in the separator, the furnace wall is not entirely designed as an evaporator heating surface. The evaporator part ends below the flue gas recirculation openings. The upper part of the combustion chamber and the walls in the area of the convective heating surfaces are arranged as a superheater with vertical tubing.

Having left the evaporator helix, the steam flows via the four separators to the walls of superheater 1. The flow passes through the walls from bottom to top. Then the steam reaches the inner supporting tubes (superheater 2) which are designed as a supporting tube screen in the lower area. After this the flow passes through superheaters 3 and 4.

The superheater has a 4-lane structure because this facilitates smaller diameters and wall thicknesses of the components. In order to even out temperature imbalance in the bank stages, crossings of the individual steam lanes in the flue gas flow are planned. The superheater is equipped with two attemperator spray stages. These are located between superheaters 2 and 3 as well as between superheaters 3 and 4.

The reheater consists of two stages with interposed spray attemperators for temperature control. The steam passes through the reheater 1 in counterflow to the flue gases. The steam reaches the reheater 2 inlet headers via four connecting lines with built-in spray attemperators. Contrary to reheater 1, the steam flows through the reheater end stage in parallel with the flue gases. Figure 20 provides a

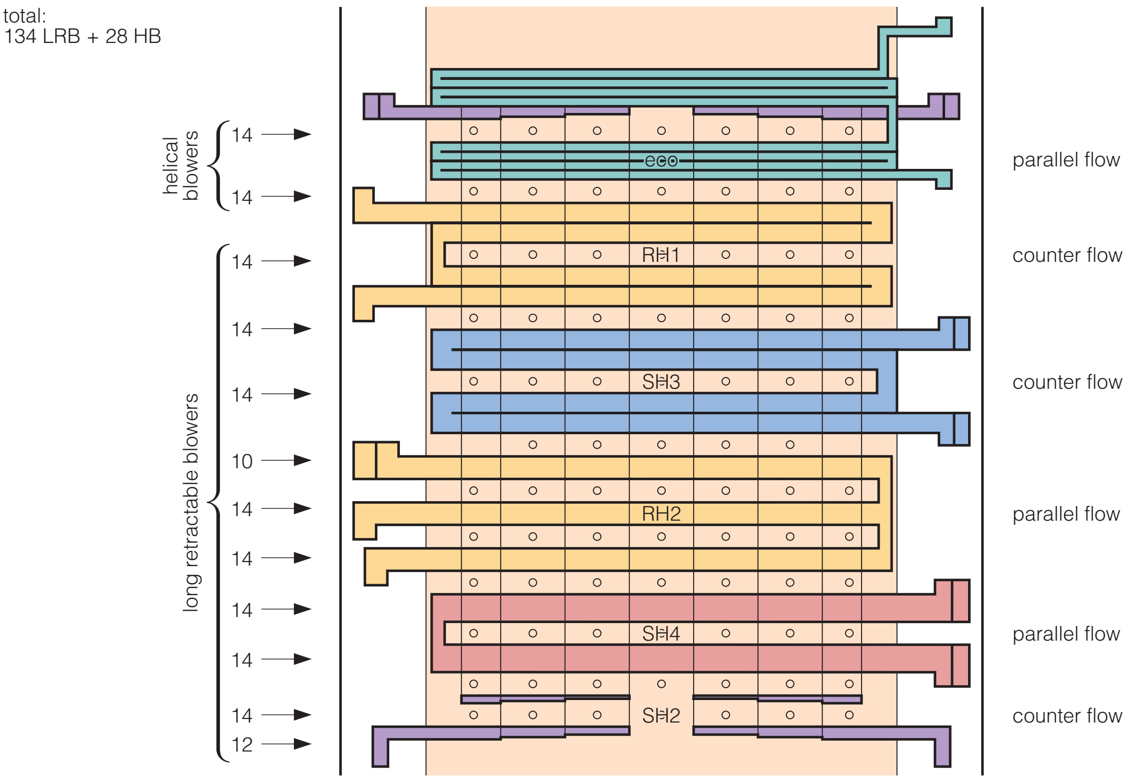


Figure 20 The arrangement of heat exchangers and sootblowers (Habermann and others, 2004)

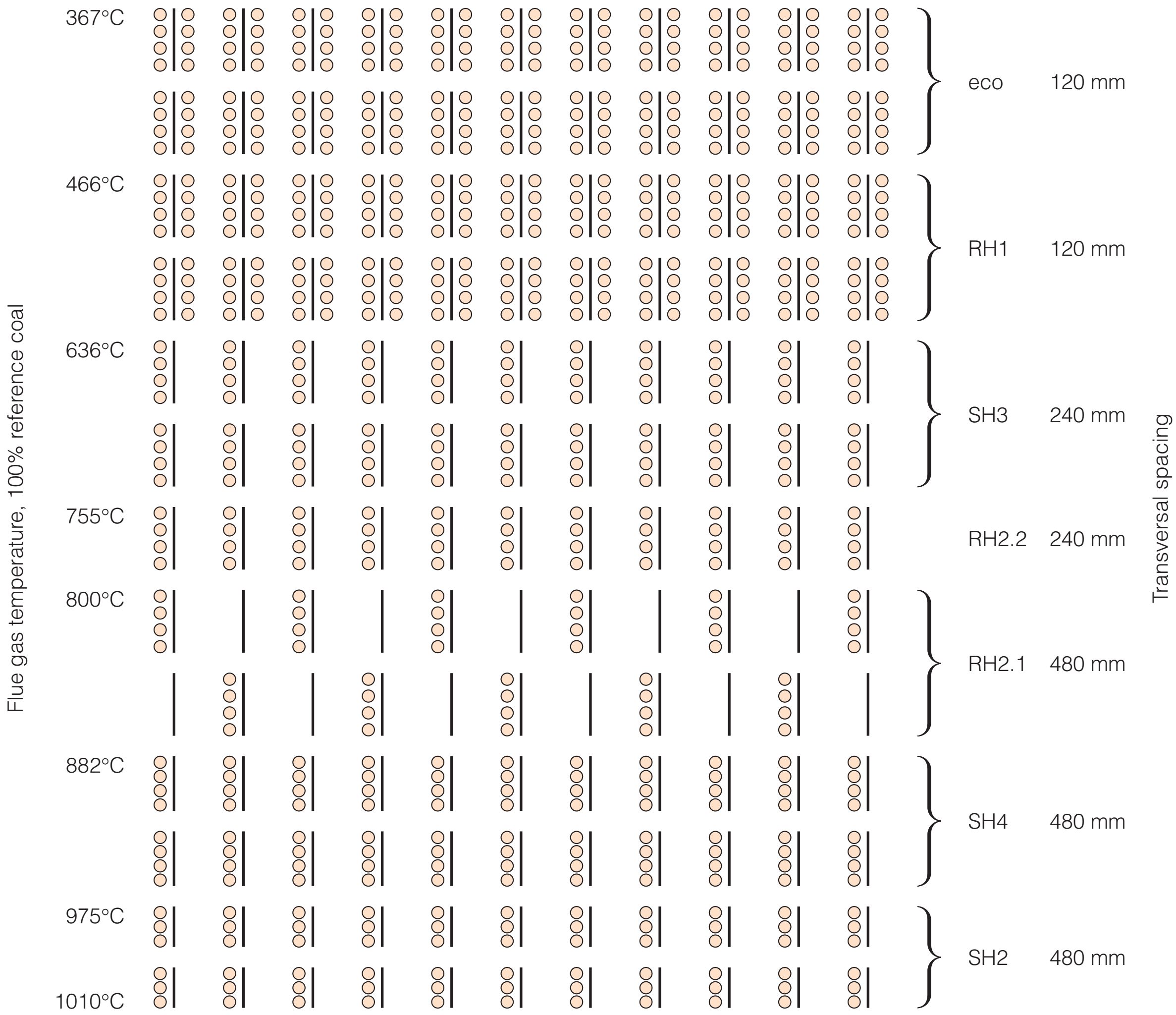


Figure 21 Transversal spacing of the heat exchangers of a BoA boiler (Habermann and others, 2004)

diagrammatic view of the arrangement of the heating surfaces and sootblowers in the upper part of the steam generator.

The outlet and inlet headers of the reheater end stage take half of the total boiler width to minimise lane imbalance. Additional temperature imbalance in the lines to the turbine caused by hot inner and cold outer lanes is hence prevented.

The spacing of the individual heating surfaces with the corresponding flue gas temperatures can be seen from Figure 21. Small bank heights are used to facilitate cleaning by the sootblowers especially for the heating surfaces located directly above the furnace. The smaller the width spacing of the heating surface the easier it is to implement low bank heights. Therefore, a width spacing of 480 mm has been chosen for the lowest heating surfaces. Experience gained with the existing boilers shows that this lateral spacing does not result in problems such as closing-in or similar effects (Habermann and others, 2004).

For BoA 2 and 3, due to the large combustion chamber of boilers, the superheater 1 wall outlet temperature during once-through operation is between 480°C and 490ºC. This is the inlet temperature of the inner supporting tubes as well. During once-through operation, the live steam temperature is kept at a constant 600ºC for a live steam flow of between 45% and 100% load. The reheater outlet temperature is controlled by means of a spray attemperator to 605ºC with combustion of reference coal within a live steam flow of between 67% and 100% (Habermann and others, 2004).

4.4.4 Primary measurers for NOx emissions control

In lignite-fired power plants, the NOx emission limit values can be met by primary measures without the need for SCR or SNCR. The aim of primary measures is to reduce NOx formation in the combustion process directly in the furnace. Primary measures include:

- reduction in excess air;
- air staging;
- vapour separation, fuel compression (fuel staging across burner height);
- flue gas recirculation;
- low NOx burners (*see* Section 4.3).

These primary measures are supplemented in individual cases by further technical optimisations such as single burner control and minimising air leakage.

4.4.5 Reduction in excess air

A reduction in the overall excess air at the exit of the combustion chamber results not only in increased boiler efficiency, but also a reduction in NOx emissions. Today, for new plants with capacities of 900 to 1000 MWe the air/fuel ratio is designed as 1.15 to 1.2 at full load at the exit of the combustion chamber. For existing plants with capacity of 300, 500 and 600 MWe, air/fuel ratios of 1.15 to 1.28 are used (VGB, nd).

4.4.6 Air staging

Air staging allows a reduction in the stoichiometry in the main combustion zone, on average 0.9 to 0.98, so that coal combustion radicals form in the less than, or near, stoichiometric combustion. These radicals then react with the NOx formed from coal combustion and convert the NOx into molecular nitrogen. In order to reduce the NOx to the greatest extent, such combustion zones should be designed with sufficient space and residence time.

The modern large steam generating units are designed with relatively low combustion chamber end temperatures. This leads to relatively large combustion chambers with long residence times. For retrofitting an existing plant, the potential for NOx reduction by air staging is strongly affected by the combustion chamber end temperature fixed by original design. When retrofitting existing steam generators, air staging should be implemented including the installation of burn-out zones in the bulkhead of heat exchangers. The residence time required can be obtained by moving the fuel injection to the lower burner levels.

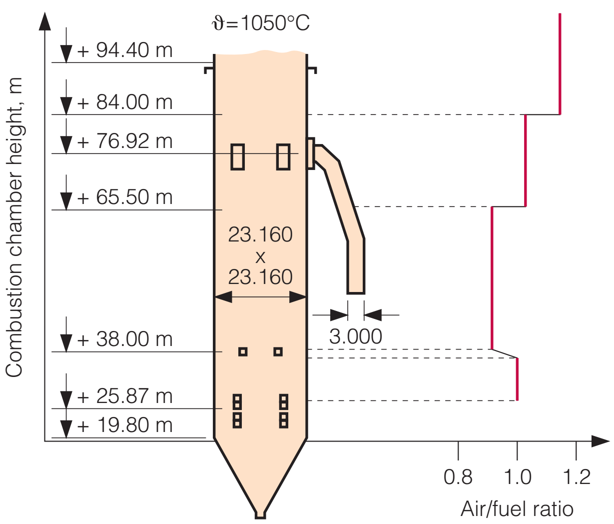


Figure 22 Air/fuel ratios at different combustion chamber height designed for BoA 1 (VGB, nd)

Sub-stoichiometric operation is limited by: the limit values for CO emissions, the increased unburnt carbon in fly ash, the risk of increased heating surface build-up, and the risk of furnace wall corrosion when consuming high sulphur coal (S >0.8%).

In general, air staging for lignite combustion can be illustrated in Figure 22. The main burner region is operated with an air/fuel ratio of about 0.9–0.98 (including vapour burners where available). The OFA (overfire air) 1 increases the air ratios to about 1.0. The distance between the main burners and OFA 1 ensures a sub-stoichiometric range for NOx reduction. The OFA 1 starts to reduce the excess CO. The previous operating experience showed that in the main combustion zone where the combustion temperature is around 1000–1300°C, there is an increasing risk of high temperature corrosion under reducing conditions if the sulphur content in lignite is greater than 0.8%. This high temperature corrosion is caused by H_2S.

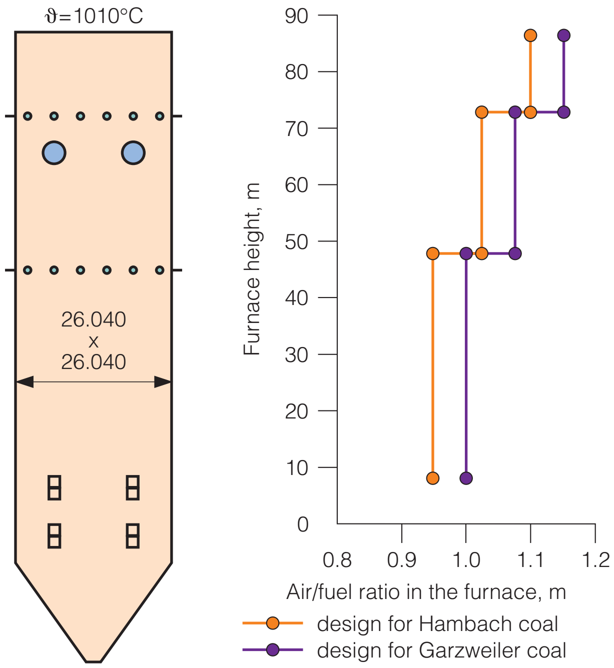


Figure 23 Air/fuel ratios at different furnace height for two lignite coals (Habermann and others, 2004)

The distance between the main burners and lowest OFA must be sufficiently great so that combustion of the volatiles is more or less completed. If the lowest burn-out air level is in an area where the burn-out of volatiles in the sub-stoichiometric range is not complete, the remaining radicals are then oxidised by addition of oxygen and the reduction of NOx is terminated prematurely causing an increase in emissions.

The adjustment of air/fuel ratio is primarily dependent on the combustion and ashing behaviour of the lignite. Figure 23 shows the air/fuel rations designed for a BoA unit burning Hambach lignite and Garzweiler lignite.

The OFA increases the total air ratio in stages. The distribution of OFA levels must also ensure sufficient residence time.

The air jets for combustion air should be arranged so that the total cross-sectional area is covered. This is crucial in order to minimise unburnt matter and for CO combustion (VGB, nd).

4.4.7 Fuel compression, vapour separation

In order to reduce NOx emissions from existing lignite plants, changes to the existing firing systems can be made. For retrofitting existing lignite-fired units, there are three feasible firing systems for primary NOx emissions control (RWE Power International, 2006):

- Direct combustion with reduced burner row height resulting in a more concentrated fuel area and separated air staging. This concept is appropriate for large steam generators with long residence times in the combustion chamber.
- Direct combustion with reduced burner row height resulting in a more concentrated fuel area and separated air staging combined with additional flue gas recirculation. This concept is the most variable and can be used for all sizes of steam generators. In flue gas recirculation, cold flue gas is recirculated from downstream of the ESP and injected into the furnace via separate nozzles arranged above the burner row. This increases the mixing of the reactants even in the case of short residence times. Combustion burn-out is delayed by the addition of the flue gas.
- Modified vapour burner concept. Direct combustion with a vapour separator downstream of the mill to divide the fuel/carrier gas mixture to the main and vapour burners and air staging across the combustion chamber height.

Both fuel compression and vapour separation ensure that more concentrated pulverised fuel streams are registered in the combustion chamber and, at the same time, the entry area of the majority of the pulverised fuel mass is shifted to the lower combustion chamber area. As a result the sub-stoichiometric reaction is prolonged. With fuel compression, at a constant ratio of fuel mass flow to primary gas flow the effective overall burner row height is reduced by shutting off some of the burners. This results in an increase in the burner row load. In vapour separation, fuel-rich and fuel-lean stream are created. The fuel-rich stream flows through the lower main burners whilst the fuel-lean stream is either injected through the remaining top burners or by additional vapour burners above the main burners. The vapour burner concept has a similar effect to that of flue gas recirculation.

When lignite with very high moisture content is burned without a pre-drying system, vapour separation is used to improve lignite ignition and combustion. As discussed in Section 4.2 the degree of vapour separation can be set by using mills with vapour separation classifier. Such an example is shown in Figure 24. In a vapour combustion system, the vapour and main burners on different combustion chamber points or tangent circles should be designed to improve the mixing conditions. Therefore, the vapour combustion combines the advantages of fuel enrichment in the lower chamber section with those of flue gas recirculation in the middle of the combustion chamber. For conversion of the existing facilities with pre-designed low chamber height (thus short residence time) to low NOx boilers, the vapour combustion system is particularly advantageous if the use of flue gas recirculation is to be avoided (VGB, nd).

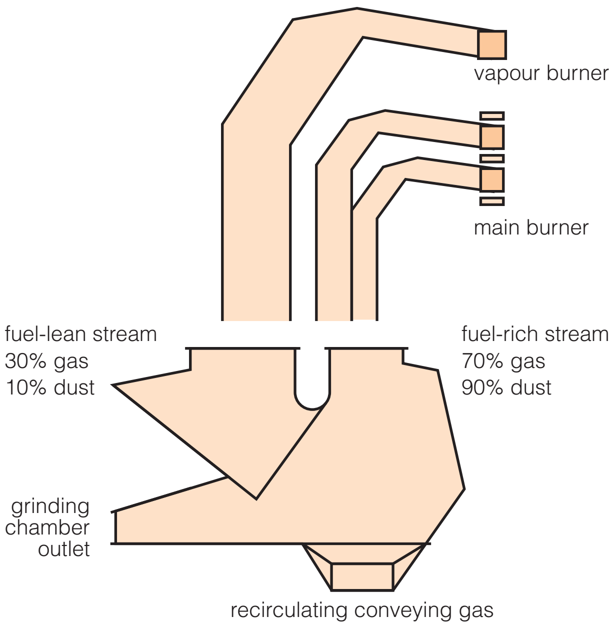


Figure 24 An example of vapour separation (VGB, nd)

Following the conversion of existing lignite-firing units to low NOx combustion in Germany, individual optimisation was required in all plants. This optimisation was made empirically. The firing system conditions are more onerous and small changes in the air distribution and other operational settings of the plant can have serious implications for the NOx emission behaviour (RWE Power International, 2006).

The fuel compression, vapour separation concept can also be applied to new lignite plants. In the BoA unit 1, nearly complete gasification of lignite in a hot pyrolysis zone in the area of the furnace centre is achieved through the use of high fuel concentration in the burner row area. The use of mills with classifiers separates the fine and coarse fuel particles for the main and reburning burners. The good reaction conditions and the extended burn-out path for the coarse fuel particles lead to nearly complete combustion, thus considerably reducing the tendency towards slagging in the upper furnace and convectional heating surface area (Heitmüller and others, 1999).

4.4.8 Flue gas recirculation

The flue gas recirculation fulfils two tasks in NOx reduction: 1) compensating the lower-than-designed gas mass flow due to the lower air ratios. This applies to retrofitting existing plants in terms of heat transfer in the convection heating surface; 2) intensive mixing of sub-stoichiometric flue gas atmospheres to improve the reaction conditions for the radicals while lowering the temperature. The extraction/discharge point of the flue gas is located after the particulate control device and before the FGD. The undesulphurised flue gas is transported back into the furnace between the burners and the OFA 1 using an additional fan.

Flue gas recirculation is normally used only for existing plants with short residence time, where the implementation of air staging and lower air/fuel ratio would cause problems as a result of combustion losses and CO formation. The potential reduction in NOx emissions is approximately 15-30 mg/m^3 at about 10–15% flue gas recirculation.

Flue gas recirculation can help to reduce the furnace exit gas temperature. Thermally, a flue gas recirculation system is necessary if the heat transfer balance between radiative and convective heat transfer must be manipulated for specific operating conditions. However, the frequent lead-in and shut-downs of the recirculation fan lead to severe corrosion in the entire piping system due to operation under acid dew point, and therefore air-flushing and -purging are required. The increased demand on the induced draft and recirculation fan as well as a greater flue gas loss in the boiler reduces the net unit efficiency. Furthermore, the flue gas recirculation system is operated under positive pressure. Accordingly, high standard technical design to avoid flue gas leaks is required. Leaks leads to acid condensation in the insulation and other consequential damages. Because of these disadvantages, flue gas recirculation systems are not usually employed when NOx emission values can be met with other primary measures (VGB, nd)

4.4.9 Heating surface cleaning system

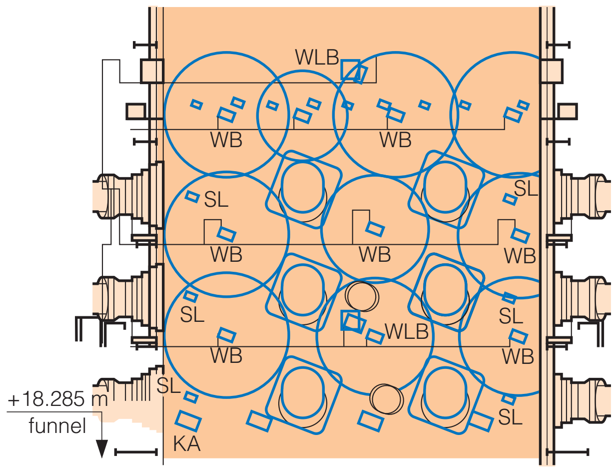


Figure 25 The arrangement of water-jet sprayers for the lignite-fired boiler at Boxberg's Unit R (Mandel and Schettler, 2007)

The combustion chamber requires state-of-the-art cleaning devices, especially when lignite with a high slagging tendency is burned. A combination of water lances and water-jet blowers can be used. The latter are used in the main burner area, since experience from utility scale operation has shown that water-jet blowers are advantageous in those areas. The cleaning concept and the cleaning strategy can be adapted in accordance to the special requirements of the type of lignite used. Figure 25 shows the arrangement of water-jet sprayers for the 675 MWe Unit R lignite-fired steam generator at Boxberg Power Plant (Germany). The water-jet sprayers are combined with water counter-flow fans in the combustion chamber or the combustion belt area.

Figure 26 presents the cleaning arrangement for a BoA unit. The water lance-type blowers in the combustion chamber are spread over five layers with four blowers each in the radiation chamber and two additional water lance-type blowers in the area of the furnace hopper. The installation locations of the water lance-type blowers are marked as red points in Figure 26. The cleaning medium is service water with a pressure of approximately 2.5 MPa upstream of the blower. In addition to the water lance-type blowers, water-jet blowers working with a water pressure of 1.2 MPa are used in the burner row area. The arrangement of these sootblowers are shown as blue circles in Figure 26.

Long retractable sootblowers are used for cleaning of the superheater bank-type heating surfaces and economiser and reheater 1 are equipped with helical sootblowers. Their range of cleaning is illustrated in Figure 27. Each space between the tube banks is fitted with sootblowers. Superheated steam from the reheater is used as blowing medium. The sootblowers for all convective heating surfaces are

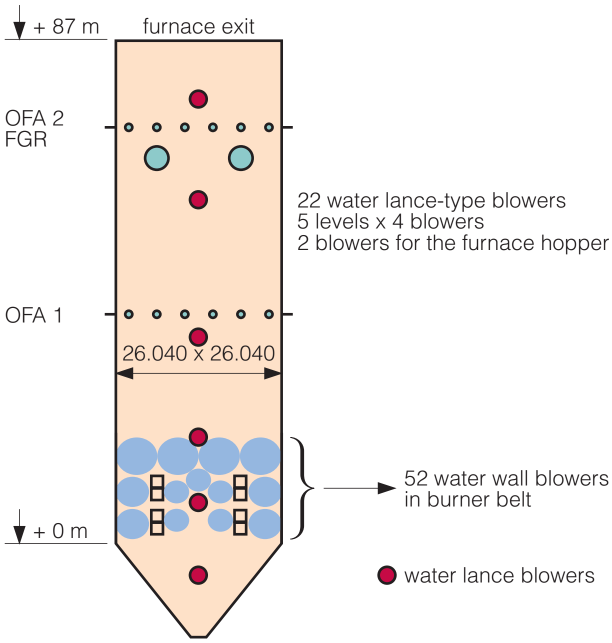


Figure 26 Arrangement of sootblowers in furnace (Habermann and others, 2004)

arranged on both sides. The blowing pressure for the sootblowers is approximately 2.5 MPa for the lance-type sootblowers and 1.2 MPa for the helical sootblowers.

The long retractable sootblowers are equipped with highly efficient nozzles which have a better cleaning effect than conventional nozzles with regard to the target blowing pressure. A further development of the currently available sootblowers with improved cleaning efficiency for applications of difficult coal is currently being pursued intensively.

An expert system for optimised sootblowing can be used. With this system, the individual sootblower is controlled as a function of the heating surface efficiencies and minimum blowing intervals. This ensures the designed heating surface efficiencies are maintained with minimal blowing. In the combustion chamber, in order to maintain the heat absorption of the wall heating surfaces under all operating conditions, the local heat flux density is monitored by means of sensors. If the heat flux density falls below a certain value, the surface assigned to the sensor will be cleaned (Habermann and others, 2004).

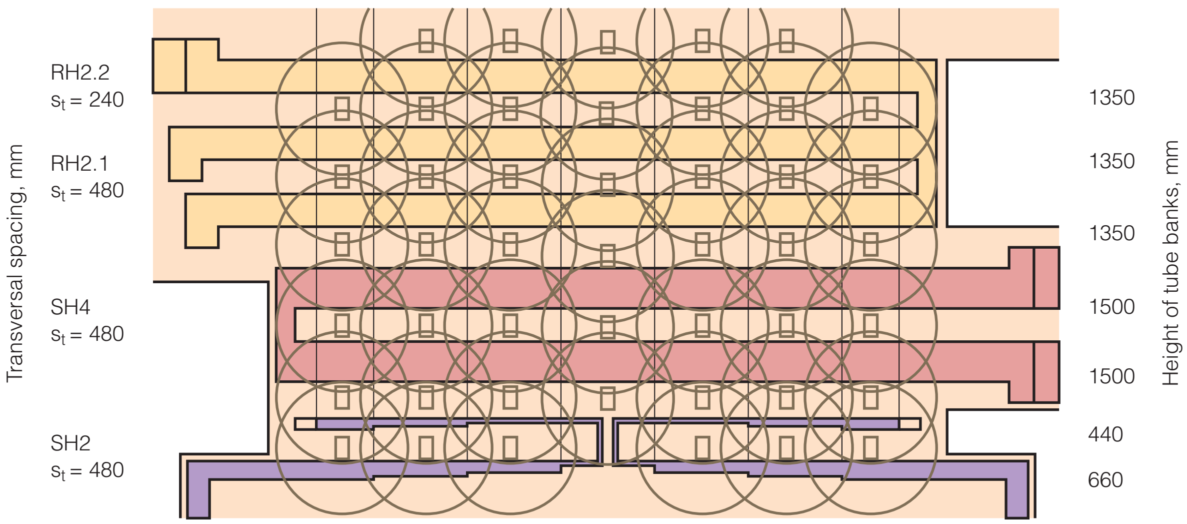


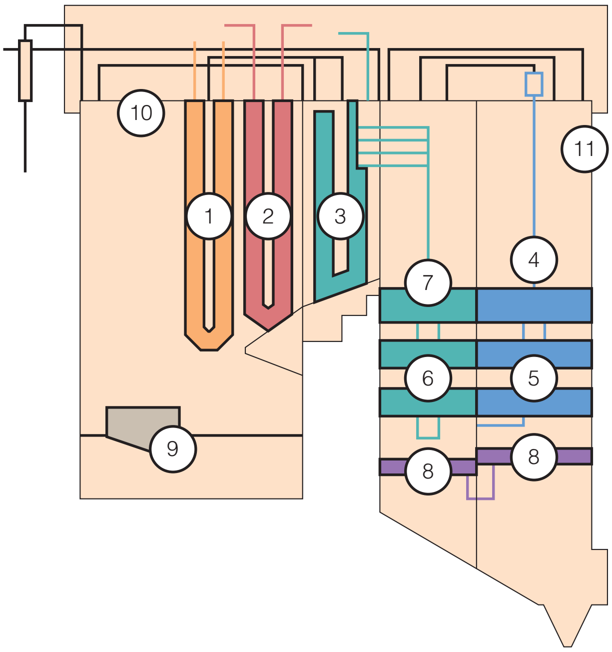
Figure 27 Arrangement of sootblowers in the convective part (Habermann and others, 2004)

4.5 Materials

The various components of the boiler experience a range of temperatures, pressures and corrosive atmospheres, and oxidation conditions. For a modern large SC steam generating unit, due to the high steam conditions and the high weight load, materials used must withstand high temperature and pressure in oxidising and corrosive environments in accordance with their application. A practical limitation to the higher steam pressure and temperatures that can be achieved in a boiler is the availability of boiler materials that can withstand these elevated conditions over an acceptable service life. Currently, the best commercially available steels allow the construction of boiler plant for steam conditions of 30 MPa/600ºC/620ºC for a wide range of coals, even those producing an aggressively corrosive flue gas. The range of alloys necessary to best meet the design demands of SC steam generators covers the simple carbon manganese (CMn) steels, low alloy steels, advanced low alloy steels, the 9–12Cr martensitic family and the austenitic range with chromium varying from 18% to in excess of 25% (DTI, 2006).

As superheater tubes must be designed to operate at temperatures ~35ºC above the live steam temperatures, for steam temperatures up to ~580ºC, the metal temperature will be ~615ºC and low-alloy steel tubes such as T22 and T23 may possess adequate creep strength. However, not only do the advanced steam parameters for supercritical plant impose higher stresses on the superheater tubes, they also increase the potential rates of both fireside and steam-side corrosion. Medium-chromium (Cr) steels such as X20 can be used at these temperatures or alternatively, for corrosive coals or higher temperatures, more expensive austenitic steels such as T316 and T347 can be used.

The layout and design issues for reheater banks are similar in principle to those of the superheater banks, in particular with reference to materials and temperature limits. However, there is more scope with the reheater to increase temperatures or adopt novel designs because the reheater pressure is much lower and so the tubes are under much less stress. In addition, the reheater is normally situated behind the superheater in a region of cooler gas flow. An additional 20ºC is typically achievable in reheater steam temperatures for the same material constraints. The current maximum boiler reheat outlet steam temperature is 610ºC for lignite (PowerClean, 2004).



Refer-ence	Heating surface	Material	Design temp, °C
1	Platen SH	SA 213 TP347H/ TP310HCbN/T92*	640
2	Final SH	SA 213 TP347H/ TP310HCbN/T92*	650
3	Final RH	T22/T91/TP347H/ TP310HCbN/T92*	680
4	Prim SH	SA 213 T91	550
5	Prim SH inlet	SA 213 T23	530
6	RH inlet	SA 210C	470
7	RH	SA 213 T12	540
8	Economiser	SA 210C	375
9	Water wall	SA 213 T12/T23	515
10	Furnace roof	SA 213 T23	510
11	Rear cage	SA 213 T23	510

* SA213 T92 used for outlet tube stub connections

Figure 28 Advanced supercritical tube materials (30 MPa/600°C/620°C) (DTI, 2006)

In thick-sectioned components such as steam pipes and headers, ferritic steels, from carbon steel up to 12% Cr X20CrMoV121 (Mo: molybdenum; V: vanadium), have been used for steam conditions of 25 MPa/560ºC. Here, the steam lines are normally now manufactured from X20CrMoV121. Materials with even higher creep strength will be needed for thick-section components under more advanced steam conditions and P91/T91/F91 are suitable for such use up to ~30 MPa/580–600ºC (PowerClean, 2004). Figure 28 shows the materials used for heating surfaces of Mitsui Babcock's SC boilers.

Figure 29 illustrates the alloys selected for the heating surfaces of a BoA steam generator. The heating

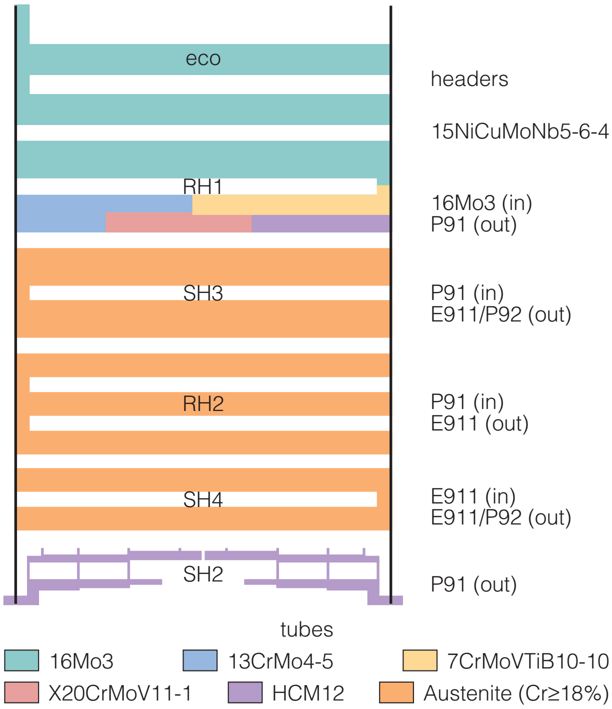


Figure 29 Alloys selected for the heating surfaces of BoA boilers (Habermann and others, 2004)

surfaces are coloured to reflect the material selection. The colour assignment of the selected materials is shown on the left and the header materials are listed at the bottom of the figure. The economiser is made completely of 16Mo3. Reheater 1 consists of the materials 16Mo3, 13CrMo4-5, 7CrMoVTiB10-10 and X20CrMoV11-1. With chromium content of 12% the material X20CrMoV11-1 has higher corrosion resistance than 7CrMoVTiB10-10 and is therefore chosen for the reheater outlet. The material used for the superheater 2 supporting tube screen is HCM12, which is a martensite with 12% of chromium and hence has higher strength values than X20CrMoV11-1. The last two superheaters and the reheater end stage are made of austenite. For reasons of corrosion protection, the austenite material has a mean chromium content of at least 18%.

Due to the high steam temperatures and the high axial loads, the material 7CrMoVTiB 10-10 is employed as a wall material at the end of the evaporator spiral and in the vertical tubing part of the membrane wall. The supporting tubes are also made of this material for the same reason.

The separator and vessel are made of P91. For the superheaters and the reheaters, from the reheater 1 outlet onwards, martensitic 9% chromium steels P91, E911 and P92 are used as header materials. Whether E911 or P92 would be selected for the superheater 3 and live steam outlet header would depend on the final strength values of these materials (Habermann and others, 2004).

There have been a number of concerted R&D programmes dedicated to development of advanced high-temperature materials that allow the adoption of even higher steam conditions for PCC units. For example, the AD700 project in Europe, aims at the construction and operation of a 500 MW USC PCC demonstration plant (called 50plus) with a net efficiency of over 50% and steam conditions of 35 MPa/700ºC/720ºC. It has a strong focus on development of nickel-based alloys for USC steam conditions of >37.5 MPa/700ºC through testing work in its COMTES700 testing facility. A similar programme funded by the US DOE is evaluating materials to achieve steam conditions of 35.2 MPa/760ºC/760ºC/760ºC. The UltraGen II programme is one of EPRI's UltraGen Initiative projects which aims at a 750 MW 1300°F (704.4°C) Series USC plant design. In 2008, EPRI published the results from Phase I of an engineering and economic evaluation for such plants fired with subbituminous coal. Similar results for lignite and bituminous coal will be reported in Phases II and III of the study. The report concluded that the high-nickel alloys used in the boiler and steam turbine necessary for achieving these higher steam conditions were at an advanced stage of development and were expected to be available to support construction of an UltraGen II demonstration plant within a few years (Dong, 2011).

4.6 Turbine system

The basic construction of single reheat large steam turbines for coal-fired power plant was established over 30 years ago. This construction, designed originally for operating at conventional steam conditions, has achieved very high standards of reliability, availability and operational flexibility through continuing development and feedback of operating experience. Today, turbo-sets for SC and USC steam power plants are available for gross power outputs from 600 to 1200 MWe per unit. A typical turbo-set comprises three separate turbine modules operating at different pressure and temperature levels: high pressure turbine (HP), intermediate pressure turbine (IP) and, depending on the cooling water conditions, one, two or three low pressure turbines (LP).

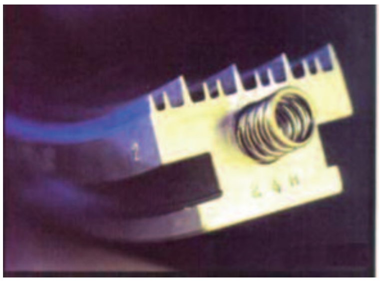
Nearly 2 percentage points of the efficiency gain in recently built large lignite-fired power plants comes from advances in steam turbine design. In today's state-of-the-art HP and IP turbines, all internal stationary components are being replaced with a single, fully integral casing. The unique features of the casing design provide the control of the inner casing's thermal distortion, resulting in maintaining designed clearances and obtaining the highest possible efficiency at running speed.

R&D in the field of steam turbine blading has accelerated rapidly in recent years through the use of CFD models. The modern HP and IP blade paths are designed using advanced airfoil shape (*see* Figure 30), overall blade path thermodynamic optimisation and enhanced sealing to provide improved efficient performance for the available space. This advanced airfoil design has a considerable advantage over the previous generation of the typical parallel-sided airfoil, allowing the airfoil shape to be enhanced to the varying steam conditions between the base and tip of the blade.

The drum-type HP/IP blade construction features an integrally shrouded blade design concept. The integral shrouds provide two basic functions: first, they form a circumferential steam path boundary allowing efficient seal designs to be utilised; and second, they provide individual blade tip support between neighbouring blades in each blade row.

The seals for the HP, IP and LP dummy pistons are comprised of a combination of both spring back and retractable seal segments. Retractable seals provide small radial clearances during operation (closed position) and large radial clearances in the open position. These types of seals minimise wear and optimise performance of the machine (Cheski and others, 2005; Quinkertz and others, 2008; DTI, 2006). Examples of advanced turbine designs are shown in Figure 30.

a) Retractable seal



b) Integrally shrouded tee-root blade

c) Dimensional airfoil shape blades

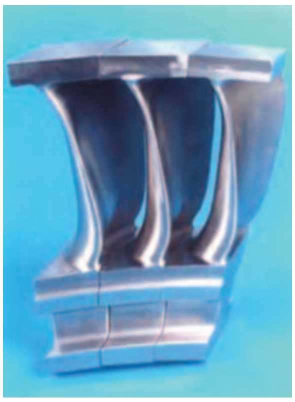


Figure 30 Examples of efficiency-increasing measures related to steam turbine (Cheski and others, 2005)

4.7 Waste heat recovery and utilisation

The waste heat recovery and utilisation systems ensure that the highest possible amount of the heat arising in the combustion of lignite is integrated into the process and exploited in power generation. Figure 31 shows the waste heat recovery and utilisation system used in BoA 1 plant. At full load the flue gases produced by the lignite combustion leave the furnace at a temperature around 1050ºC. After having passed the convection heating surfaces arranged above the furnace, the flue gases are conveyed in the downward open pass to the two parallel rotary air heaters and to the air heater bypass economiser (lubeco) which is also arranged parallel to these two rotary air heaters. The flue gases are joined underneath the two rotary air heaters or at the side underneath the lubeco and then conveyed to the two electrostatic precipitators, the two flue gas coolers and then to the FGD system.

The flue gas coolers are arranged upstream of the FGD plant for flue gas heat recovery. The flue gas coolers reduce the flue gas temperature from 160ºC to the minimum temperature of 100ºC for an effluent-free operation of the FGD plant and keeps this temperature constant over all operating conditions. This arrangement utilises the low grade heat in the cycle process leading to improved energy efficiency. Approximately 80 MJ/s of heat is recovered and transferred to the process of steam generation through the use of the flue gas coolers. In the first stage the heat is recovered via a water cycle in a feedwater/air heater. As the quantity of heat flux to be absorbed by the combustion air in the rotary air heater in the second preheating stage is now reduced, a part of the flue gas heat can be utilised for the preheating of feedwater and condensate. About one-third of the flue gas, with a temperature of around 350ºC, is led through the lubeco which is arranged in bypass to the rotary air heaters, where it dissipates the heat in the first section to a partial stream of the feedwater in parallel with the HP heaters as shown in Figure 31.

In the second section, steam is generated by natural circulation for heating the penultimate LP heater.

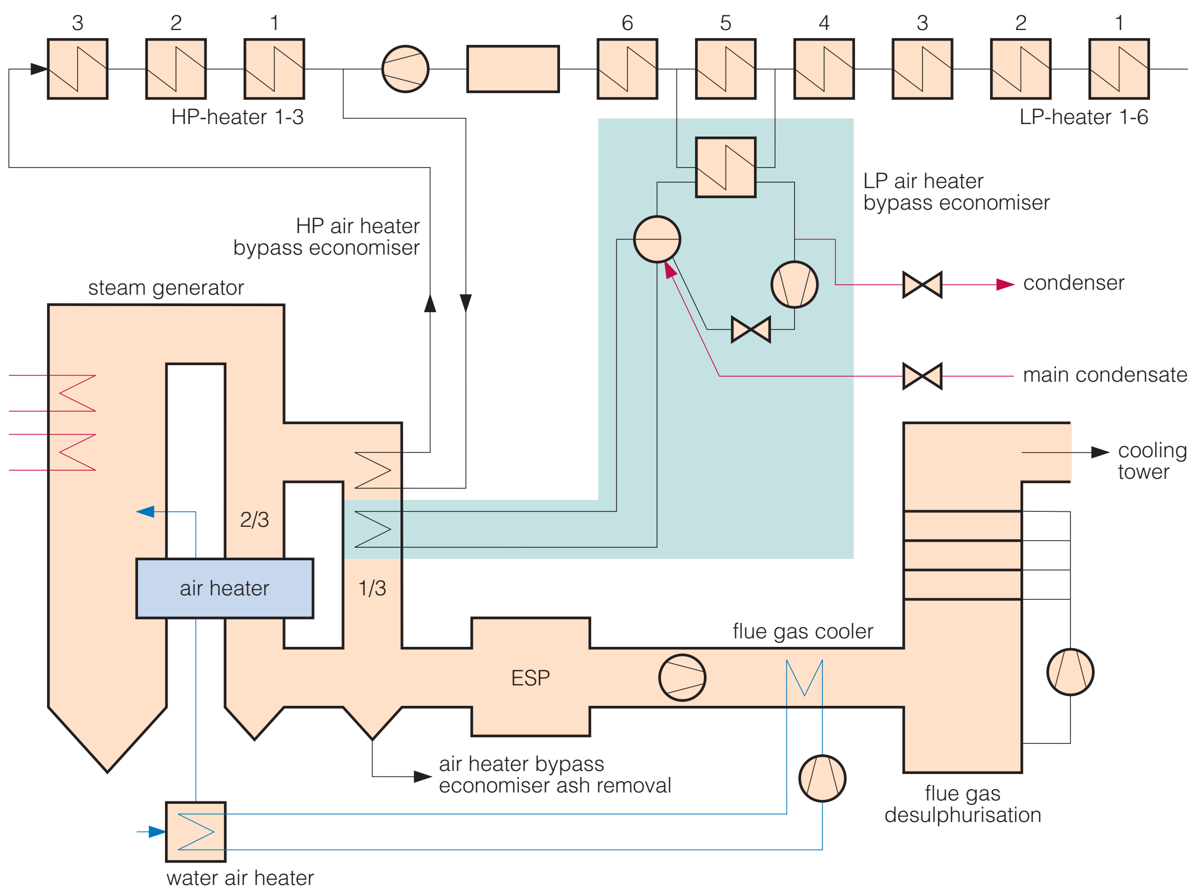


Figure 31 Extensive heat transfer systems for higher overall efficiency (RWE, 2011)

The flue gas temperature downstream of the air heater bypass is 160ºC. With this arrangement, less steam needs to be extracted from the turbine for condensate and feedwater preheating (Heitmüller and others, 1999).

The waste heat recovery and utilisation system used in BoA 1 plant contributes to more than 0.9 percentage points of total net unit efficiency gain.

4.8 Impact of lignite characteristics

Coal type and quality affect the design, operation, performance of the plant and hence its capital and operating costs. The main properties of a lignite coal that affect firing system design include:
- heating value;
- ash content, ash characteristics;
- moisture content;
- volatile matter;
- grindability (Hardgrove Grindability Index).

Considerable variation in the lignite properties may require an adjustment of the operating conditions of the firing system and the mills.

The milling, drying and firing systems applied to the BoA Plus power plant are developed in accordance with the quality of the German lignite coals burnt at the plant. When the BoA/BoA Plus technologies are employed to burn different lignite coals, adjustments and optimisations of these systems and in boiler design will be required depending on lignite characteristics. RWE recently carried out a technical and economical analysis of applications of the BoA plant concept boiler design to Greek lignites. The characteristics of three Greek lignites and a German lignite are compared in Table 6. It can be seen from Table 6 that Greek lignites have much higher ash contents compared to the German Rhenish lignite. The moisture content of Greek Florina lignite is lower than that of Rhenish lignite whilst the moisture content of Greek Drama and Ptolemäis lignites are comparable to that of Rhenish coal. Consequently, the Greek lignites have lower heating values than that of Rhenish lignite. The drying energy of a coal, calculated based on the coal moisture content and heating value, is an indication of the energy required to dry the coal. As shown in Table 6, the drying energy of Drama and Ptolemäis coal is considerably higher compared to Rhenish coal. The drying energy of Drama coal is twice as high as that of Rhenish coal and about 30% of the fuel energy is needed for drying the coal. As a result, optimised design and special operating conditions for milling, drying and burner systems are required for Drama and Ptolemäis coal. The drying energy of Florina is comparable to the value of Rhenish coal and there should be no problem for the drying process.

Table 6 Comparison of Greek and German lignites (RWE Power International, 2006)

	Rhenish	Drama	Ptolemäis	Florina
Water content, %	53.0	57.8	51.1	37.4
Ash content, %	5.0	16.1	17.3	27.2
Net calorific value, MJ/kg	8.70	4.38	5.36	7.89
Flue gas mass, kg/MJ	0.54	0.69	0.62	0.51
Specific coal mass, kg/MJ	0.115	0.228	0.186	0.127
Ash mass, g/MJ	5.74	36.8	32.2	34.5
Boiler efficiency, %	93.0	87.0	88.6	89.7
Auxiliary power consumption, %	5.0	6.0	6.0	6.0
Unit net efficiency, %	43.3	39.3	40.0	40.5

However, Florina coal contains a higher content of xylite elements, which may cause problems in the milling system in achieving the required grinding fineness and problems in the furnace because xylite particles need a longer burn-out time.

Another parameter that affects the boiler design is the mass flow rate of flue gas. The mass flow rates shown in Table 6 are determined by the fuel heating value and based on 10% excess air. Due to the high moisture content and low heating value, the Drama and Ptolemais coal have significantly higher flue gas mass flow rate whilst Florina coal has a similar flue gas mass flow rate compared with that of Rhenish coal. The increase in the specific flue gas mass flow rate results in a larger absolute mass flow of flue gas in the boiler for the same fuel heat consumption. Therefore, the dimensions of the boiler have to be increased and the heat transfer between the flue gas and boiler heating surfaces has to be modified. The higher volume of flue gas also has an influence on the firing system and the FEGT.

A stable flame can be achieved by optimised burner design and the boiler tube heating surface must be increased in order to absorb the heat of the flue gas and decrease the waste gas temperature.

The higher flue gas mass flow of the Greek lignite requires a different design of burner layout to ensure an adequate flame development and behaviour in order to achieve stable firing and sufficient NOx reduction. This behaviour depends on the flue gas and air velocity leaving the burner and the coal to flue gas ratio importing the firing heat to the burner mouth. The relation between these items is very important for the ignition and burning of the lignite. Due to the higher coal-flue gas ratio used, and other factors such as greater coal mass flow, the burner areas must be increased to ensure equal velocities. This will result in an increase in the electrical power demand of the induced draft fans, leading to a decrease in net boiler efficiency. The capital cost will also increase, due to the enlargement of the firing system, the heating surfaces and the boiler dimensions.

It is evident from Table 6 that a boiler burning Drama coal will have larger specific fuel mass flow, nearly twice as much as that of a boiler burning Rhenish coal. This directly affects the milling system and the coal handling plant, increasing the capacities and therefore the capital cost. The power consumption of the drive motors will also increase resulting in a reduction in the net efficiency of the power plant.

The high ash content of all three Greek lignites means higher ash mass flow leading to an ash handling plant three times larger then that for the Rhenish coal. The high ash mass flow also results in an increase in the unburnt carbon in the furnace bottom ash and in the fly ash. In addition, heat dissipation occurs due to the increased mass flow of discharged ash. Consequently, the boiler efficiency is reduced and the auxiliary power consumption is increased as shown in Table 6, leading to higher capital and operating costs (REW Power International, 2006).

Further technical investigations are necessary in order to apply the BoA technologies to the Greek lignites and to lignite coals from other parts of the world, especially for coals with rather different characteristics from that of the Rhenish lignite.

4.9 Case study: BoA 2&3

The RWE's Neurath Power Station units F and G, also referred to as BoA 2 and 3, have a gross capacity of 1100 MWe each (1050 MWe net) and a net efficiency of over 43%, similar to that of Niederaussem unit K (BoA 1). The high efficiency of the BoA 2 and 3 units at Neurath can be ascribed to:

- the steam conditions (600/605ºC); the steam turbine technology; the nine-stage feedwater preheating system;
- the maximisation of waste heat recovery from the flue gas,
- minimisation of auxiliary power needs, for example, through use of turbine driven feedwater pumps.

The key data for BoA 2 and 3 are summarised in Table 7.

Table 7 Key data for BoA 2 and 3 (Elsen and Fleischmann, 2008)

Owner/operator	RWE Power AG
Fuel	domestic lignite
Cooling system	cooling tower with natural draught
Installed capacity, MWe	1100 (gross), 1050 (net)
Net efficiency, %	>43
Steam generator	
Type	once-through, tower
Steam flow, t/h	2870 (2960 maximum)
Steam pressure, MPa	27.2 (28.04 maximum)
Steam temperature, °C	600
Furnace capacity, MWt	2392 (2800 maximum)
Raw lignite input (guarantee lignite), t/h	820 (1326 maximum)
Steam turbine	
Type	STF 100
Number of modules (casings)	4
Steam pressure, MPa	25.9
Steam temperature – inlet/reheat, °C	595/604
Speed, rpm	3000
Generator	
Type	GIGATOP
Rating, MVA	1333
Power factor	0.825
Frequency, Hz	50
Terminal voltage, kV	27
Excitation system	static excitation system
Cooling system	hydrogen plus water
Condensing plant	
Circulating water temperature, °C	18.2
Condenser pressure, kPa	4.8
Tube material	stainless steel
Feedwater heating plant	
Number of feedwater preheating stages	9
Number of feedwater heaters	8
Number of feedwater deaerating tanks	1
Feedwater inlet temperature, °C	292
Main pumps	
Condensate extraction pumps, %	3 x 50
Feedwater pump	1 x 100% main turbo driven feedwater pump plus 2 x 40% start-up motor driven feedwater pump
Circulating water pumps, %	2 x 50
Polishing plant	yes
Main transformers	
Rated output, MVA	2 x 1100 (per unit)
Primary/secondary, kV	420/27
Standby transformer	
Rated output, MVA	90/45/45
Primary/secondary, kV	110/10.5/10.5

The units burn lignite that is supplied by RWE's own local opencast mines at Garzweiler and Hambach. The lignite mills pulverise the lignite and, to lower its high moisture content (48–60%), dry it using hot flue gases taken from the furnace. Next, together with heated air from the flue-gas air heater, the pulverised lignite is blown into the combustion chamber of the steam generator.

Table 8 Technical data of BoA 2 and 3 (Elsen and Fleischmann, 2008)

Firing thermal capacity, MWth	2392 (max 2800)
Lignite feed, t/h	820 (max 1300)
Main steam	27.2 MPa/600°C
Hot reheat steam	5.5 MPa/605°C
Total dimensions, m	170 x 100 x 100
Dimension of boiler, m	142 x 26 x 26
Heating surface, m^2	146,000

The boilers are of once-through, single pass type each having a capacity of 2392 MWth (2800 MWth maximum). They are the largest lignite-fired boilers in the world, with the highest steam mass flows, supercritical steam pressures and steam temperatures ever reached for lignite. The boiler dimensions and other technical data are shown in Table 8.

The process flow of the BoA 2 and 3 is shown in Figure 32. The firing system and the burner arrangement implemented in BoA 2 and 3 have been described in detail in Section 4.4.1. The lignite combustion temperature is about 1200ºC. The hot flue gas that emerges during combustion flows through the steam generator from bottom to top. In the process, it transfers heat to the outer walls, which consist of tubes, and to the tube banks suspended in the flue-gas flow. Heated feedwater flows through these tube systems and is evaporated and superheated. The detailed descriptions of the thermal design of the BoA boilers can be found in Section 4.4.3.

After passing through the topmost bank of heating surfaces, the flue gas is redirected to the downward open-pass duct and distributed across the two flue-gas air heaters to preheat the combustion air. After flowing through these heat exchangers, the flue gas (cooled from about 350ºC to 160ºC) is conducted in two parallel lines to flue gas cleaning systems. The latter consist of electrostatic precipitation for particulate removal, followed by FGD. A further portion of the remaining flue-gas heat is removed from the flue gas before it is fed into the FGD plant via flue gas coolers and transferred via a heat-transfer cycle to a part-flow of the condensate in the feedwater heating section. This lowers the flue-gas temperature to 125ºC before it enters the FGD system, which employs polypropylene and concrete for the scrubber wall materials.

Combustion is subject to constant monitoring and adjustment of the lignite and air feed, so that it is optimised and NOx production minimised. The legally prescribed emission limit values for NOx (200 mg/m^3) can be easily met by these combustion measures alone, without additional post combustion de-NOx systems.

The main steam produced by the steam generator has a pressure of 27.2 MPa and a temperature of 600ºC and is initially expanded to 5.87 MPa in the turbine's high-pressure section, where the temperature falls to 356ºC. This steam is conducted back to the steam generator and superheated again (reheated) to 605ºC. In the intermediate- and low-pressure sections the steam expands to the pressure of 4.8 Pa prevailing in the condenser, where it is precipitated as water. The cooling water is re-cooled in the cooling tower by falling as rain in continuous contact with cooling air. The cooling air required for this in the energy-efficient natural-draught tower necessitates the tower height of around 170 m.

The cooling water that evaporates during re-cooling, and the cooling water that must be discharged to avoid excess concentrations of salt, has to be replaced on a continuous basis. The make-up water is primarily from the Frimmersdorf power plant, which is treated there before it is deployed in Neurath. Alternatively, treated water from Niederaussem can be used.

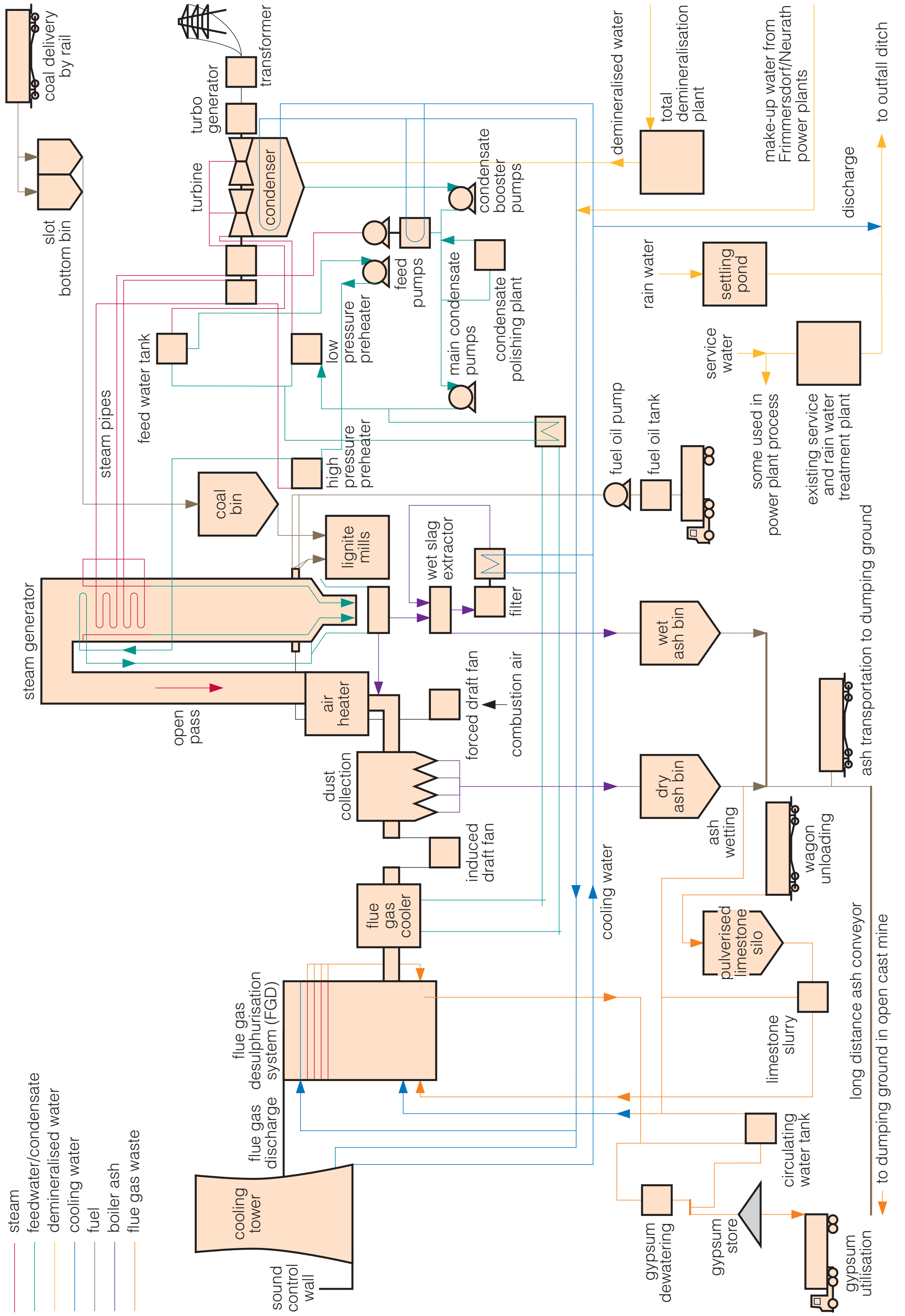


Figure 32 Schematic of the BoA 2 and 3 (Elsen and Fleischmann, 2008)

At Neurath, the steam turbines, each rated at 1100 MWe, are of the Alstom STF100 type. They employ fully flow optimised blading. A compact four casing configuration is employed: HP, IP and two LP (whereas at Niederaussem there is a three-casing LP). The two-casing four-flow low pressure turbine stage is made possible through the use of titanium 1.408 m last-stage blades – the longest last-stage blades currently offered on the world market, providing an exhaust cross-section of 13.2 m^2. The compactness of the steam turbine contributes to reduced construction costs.

In addition to reduced CO_2 emissions due to the higher efficiencies, the BoA units will also achieve specific SO_2, NOx and particulates emission levels below the limits specified in the German ordinance on large combustion plants: SO_2 – 200 mg/m^3 and a desulphurisation rate of >85%; NOx – 200 mg/m^3; CO – 200 mg/m^3; and particulates – 20 mg/m^3.

4.10 Summary

The experience of operating lignite-fired power plants in Germany has shown that lignite can be burned efficiently to produce power at competitive prices. It has been proven that lignite-fired power plants can achieve high efficiency and have good environmental performance. The RWE's BoA 1 plant has achieved net plant efficiency of >43% (LHV based). Higher plant efficiencies can be achieved if lignite pre-drying technology such as WTA is implemented. The high lignite plant efficiency is achieved by application of advanced technologies and improved engineering designs to all parts of the power plant.

Due to the considerable variation in the quality of lignite coals, careful selection of technologies and proper process and engineering designs is required to ensure lignite-fired plants achieve high efficiency, reliability and availability, good environmental performance as well as cost effectiveness. Solutions are available for particular problems relating to certain coal qualities. Research into the application of the available technologies from which power producers can select the options most suited to preferred coal types, local conditions and compliance requirements are needed. In particular, technical investigations are necessary in order to apply the German technologies to lignite coals in other parts of the world, especially for coals with rather different characteristics from those of the German lignite.

5 PC versus CFBC

Fluidised bed combustion (FBC) is an alternative to PC combustion that 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 an FBC 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. Heat in the boiler converts the limestone to lime that absorbs SO_2, removing most of it in the furnace. FBC technology offers several benefits. FBC boilers are extremely flexible, allowing a wide range of fuel qualities and sizes to be burned. Emissions of SOx and NOx are significantly reduced without the addition of expensive flue gas emissions control technology. The lower combustion temperature of an FBC boiler (800–900ºC) compared to PC combustion (1300–1700ºC) limits ash fouling and corrosion of heat transfer surfaces allowing the FBC to handle fuels that are difficult to burn in a PC boiler. Even though the combustion temperature of an FBC boiler is low, the circulation of hot particles provides efficient heat transfer to the furnace walls and allows longer residence time for combustion and limestone reaction. This results in good combustion efficiencies, comparable to PC-fired 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 impact of FBC residues (primarily ash) are not fully understood and therefore disposal requires careful consideration.

FBC can occur in either atmospheric (AFBC) or pressurised (PFBC) boilers. Two main types of fluidised bed designs can be used: a bubbling fluidised bed or a circulating fluidised bed. The fundamental distinguishing feature between these types is the fluidisation velocity. In the bubbling bed design, the fluidisation velocity is relatively low, in order to minimise solids carryover or elutriation from the combustor. Circulating FBCs, however, employ high fluidisation velocities to promote the carryover or circulation of the solids.

FBC technology has been used in the USA, Europe and Japan since the 1980s and more recently in emerging economies such as China for power generation. Circulating fluidised bed combustion (CFBC) is the predominant type of FBC used for power generation. The technology is particularly suited to low grade fuels. Despite its wide applications in power generation sector and other industrial processes, the technology is still evolving.

5.1 Advances in CFB technology

Research and development of CFBC began in Europe and 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, more than 300 coal-based FBC generating units with total capacity of around 40 GWe have been installed worldwide (IEA CCC, 2011). Today, the CFBC technology can be considered as a mature technology for power generation/cogeneration and industrial sized applications and is commercially available from multiple suppliers.

The main advantages of the CFBC technology can be summarised as follows:

- **Fuel flexibility:** 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.
- **Low emissions:** low SO_2 emissions due to efficient sulphur capture with limestone in the furnace, low NOx emissions due to air-staging and low combustion temperature, low CO

emissions due to good fuel and air mixing and uniform furnace temperature resulted from the turbulent conditions inside the furnace.

- Stable operating conditions and good turndown and load-following capability.

5.1.1 Efficiencies

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 burned 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%. When lignite is fired, the high moisture content of lignite has 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).

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/use-specific. With a subcritical cycle, the plant efficiency is of the same order as that of a PCC plant, normally between 38% and 40% on an LHV basis (Henderson, 2003; Wu, 2006) or between 35% and 38% on an 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. It adopts steam conditions of 27.5 MPa/560ºC/580ºC and has a net plant efficiency of 43.3% (LHV basis) (Jäntti and Parkkonen, 2010).

5.1.2 Availability and reliability

Over the past 20 years, the availability and reliability of CFBC boilers have been improved and are considered to be generally equivalent to PC boilers. Koornneef and others (2007) studied the availability data of FBC 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% or higher. The improvement in the CFB plants availability over the years is demonstrated in Table 9. The increased availability and reliability have been achieved by improvements in refractory

Table 9 Improvement in the availability of Babcock & Wilcox's CFB plants (Maryamchik and Wietzke, 2010)

	Ebensburg CFB, USA		CFB at Southern Illinois Uniiversity, USA		Indian Kanoria 1 (commissioned in 1996)	Indian Kanoria 2 (commissioned in 2005)	Indian Rayon (commissioned in 2006)	Indian Saurashtra Cement (commissioned in 2008)
Reported year	1991-2003	2004-2009	1997-2003	2004-2009	1997-2010	2006-2010	2007-2010	
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

system designs, fuel and sorbent feed system designs, and ash extraction equipment design that adequately address the initial problems encountered with these system components. These systems are high maintenance and can cause lower overall availability of CFB (Black & Veatch, 2007).

5.1.3 Environmental performance

One of the main advantages of a CFB boiler is the low emissions of NOx and SO_2. Typically, CFBC can achieve a sulphur retention 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.

CFBC has relatively low NOx emissions due to the low combustion temperatures and air staging. NOx emissions are only around one fifth of those produced by uncontrolled PC combustion. 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). Unlike 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).

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 lignite-fired CFBC units are shown in Table 10.

Table 10 Emissions data for lignite-fired CFBC units (Psik and others, 2005; Walkowiak and Wójcik, 2001; Jäntti and others, 2007)

Red Hills power plant, USA, 2 x 250 MWe CFBC units			
Coal characteristics, Wt%		Design	Range
Moisture		41.75	37.45–49.58
Ash		14.64	6.09–23.19
Sulphur		0.58	0.19–1.25
Fixed carbon		19.54	19.54–23.59
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; Units 4–6: 262 MWe			
Coal characteristics, wt%		Design	Range
Moisture		44	40–48
Ash		22.5	6.5–31.5
Sulphur		0.6	0.4–0.8
LHV, MJ/kg			7.1–10.2
Emissions (mg/m^3, dry flue gas at 6% O_2)			
	Units 1–3		Units 4–6
	Guaranteed	Measured	Guaranteed
SO_2	150*	84–126*	347
NOx	150*	111–126*	371
Particulate	50	3.5–17.5	50

* g/GJ

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 controls typically applied are selective non-catalytic reduction systems (SNCR) to reduce NOx emissions and dry FGD systems to reduce SO_2 emissions.

5.1.4 Scale-up

Over the last ten years, one of the significant advances of CFBC technology has been the increase in the size 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. Figure 33 shows some of the recent coal- fired CFB installations and CFB 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 33. Most of the CFBC units commissioned recently are in the range of 250 MWe and 330 MWe. The largest CFB unit in operation is the 460 MWe hard 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 CFB units will fire bituminous coal and biomass fuel and are scheduled to start operation in 2015 (Foster Wheeler, 2011; Hotta, 2011). Further scale-up of CFBC units to above 600 MWe is possible.

5.1.5 Other developments in CFB technology

Since the commercialisation of CFB technology began back in the late 1970s, there have been continuous technology innovations and improvements that are implemented into the designs to enhance performance, increase efficiency, improve reliability and operational flexibility in a cost-effective way. The main technical innovations incorporated into the latest CFB plants include:

- cooled solids separators and cross-over ducts in combination with advanced refractory systems to minimise refractory maintenance and enhance unit performance;
- integrated fluidised bed heat exchangers to increase operational flexibility to adjust furnace temperature and extend the steam temperature control range;
- fluidised bed ash coolers to reliably discharge spent bed material and recover heat;
- reheat steam bypass systems for reliable and cost effective reheat steam temperature control;
- adoption of once-through supercritical operating conditions to achieve higher plant efficiency.

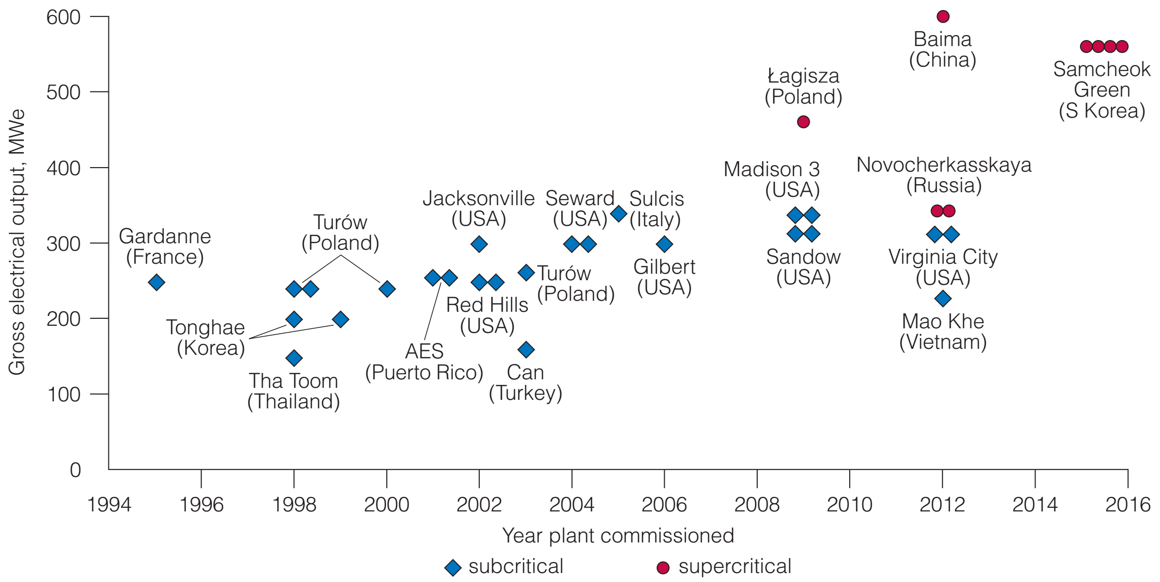


Figure 33 Recent CFB units installed, planned or under construction (Powerclean, 2004; Foster Wheeler, 2011)

The recent developments in CFBC technology and engineering designs will be reviewed in detail in a future report to be published by IEA Clean Coal Centre.

5.1.6 Future developments

Although CFBC has achieved considerable commercial success, there are a number of areas that continue to be the focus of attention. Further development in efficiency improvement, fuel flexibility, effective scale-up, reducing capital cost and CO_2 capture is needed for CFB to remain a competitive technology and gain market share in the power generation sector.

The main focus of the development of more efficient CFBC system is on increasing the capacity and the use of advanced steam cycles. 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 supercritical CFB boiler (Morin, 2003; Stamatelopoulos and others, 2005). Similarly, Foster Wheeler has developed a modular design approach allowing it to offer commercial CFB units up to 800 MWe in size for bituminous coal, or CFB units with sizes between 600 and 800 MWe for lignite depending on lignite moisture and ash content (Hotta, 2011).

In recent years, investigations into the technical feasibility and economics of CFB boilers with ultra-supercritical (USC) steam parameters have been conducted. The study of conceptual design of USC CFB boilers by Foster Wheeler found that despite the CFB's relatively low combustion temperature, the 700ºC steam temperature of advanced USC cycles can be accommodated by operating Foster Wheeler's integrated recycle heat exchanger with internal solids circulation. The physical arrangements of the 400 MWe and 800 MWe USC units reflect conventional Foster Wheeler CFB boiler configurations and can be deployed without the need for R&D work. 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.

As with PCC plants, potential carbon capture for CFBs could be accomplished by post-combustion capture. However, the nature of CFBC seems to favour capturing CO_2 during the combustion process and the oxyfuel CFB firing process is currently being developed.

5.2 CFB manufacturers and their technologies

Alstom and Foster Wheeler are currently the two largest producers of CFBC technology and both are active in various regions worldwide. In terms of the overall number of units installed and in operation, Foster Wheeler is clearly the market leader. Other suppliers include AE&E Lentjes GmbH (formerly known as Lurgi Lentjes), Babcock & Wilcox (B&W) and Kvaerner (acquired by Metso in 2007). There are also some smaller suppliers that are active in their own region such as Bharat Heavy Electricals Ltd (India), ThyssenKrupp Industries India and some Chinese boiler manufacturers.

5.2.1 Foster Wheeler

Foster Wheeler was first-to-market in both CFB and BFB technology, and recently supplied the world's largest and also the first supercritical CFB boiler. It has supplied more than 200 CFB units with a total capacity of over 10 GWe. Table 11 lists the lignite-fired CFB plants supplied by Foster Wheeler.

In early 1990s, Foster Wheeler introduced a new generation of CFB boiler with Compact CFB design.

Table 11 Reference of Foster Wheeler's lignite-fired CFB plants (Hotta, 2011)

Commissioning year	Client	Country	Capacity, MWe
2013	Kraftanlagen Power Plants GmbH (KAP)	Czech Republic	135
2009	Bechtel/TXU	USA	2 × 315
2004	BOT Elektrownia Turów SA	Poland	2 × 262
2003	BOT Elektrownia Turów SA	Poland	262
2000	BOT Elektrownia Turów SA	Poland	235
1998	BOT Elektrownia Turów SA	Poland	2 x 235
1998	CEZ as Porici Power Plant	Czech Republic	60
1998	Moravskoslezske Teplarny as	Czech Republic	40
1997	CEZ as Hodonin Power Station	Czech Republic	35
1996	CEZ as Porici Power Plant	Czech Republic	60
1994	Thai Paper Co Ltd	Thailand	25
1993	Siam Kraft Industry Co Ltd	Thailand	15
1992	Rheinisch-Westfälisches Elektrizitäts Werk AG	Germany	100
1990	KW Berrenrath	Germany	2 x 60
1988	KW Wachtberg	Germany	50
1987	Lenzing AG	Austria	25
1987	Leykam-Mürztaler AG	Austria	40

One of the distinguishing features of the Compact CFB is the compact solid separator which is formed from flat rather than curved tubing panels. In this arrangement the separator is positioned adjacent to the furnace which provides a 'compact' configuration. The boiler layout includes a pair of double vortex Compact Separators on both the furnace front and rear walls, and a series pass heat recovery area with Foster Wheeler's reheat steam bypass arrangement for reheat steam temperature control. Another innovation that enhances the Compact CFB boiler design is the integrated recycle heat exchanger INTREX which provides the additional solids cooling needed for larger boilers. The Compact CFB units installed at Turów Power Plant have eight INTREX cells which include intermediate and finishing superheater heat transfer surfaces; four cells per front and rear wall positioned to accommodate a well distributed arrangement of fuel feeders. The ability to control the rate of solids flow through the INTREX tube bundles provides increased operational flexibility for furnace and steam temperature control (Goidich and Hyppänen, 2001; Walkowiak and Wójcik, 2001; Goidich and Lundqvist, 2002)

Foster Wheeler has licensed Siemens' vertical low mass flux Benson once-through technology for use in the design of SC CFB boilers. One general feature of the Benson once-through technology is that it results in a lower water/steam side pressure drop. This reduces feedwater pump power consumption, thereby reducing the plant net heat rate. The design of the 460 MWe SC CFB unit at Łagisza, Poland integrates the Benson vertical once-through technology into the Compact CFB boiler configuration. Based on the design used for Łagisza CFB unit, ultra-supercritical steam conditions can also be adopted (Lundqvist and others, 2003; Fan and others, 2006).

5.2.2 Alstom

Alstom's CFBC technology is based on a separation system with inlet ducts that are designed to accelerate and separate the particles prior to the cyclone itself. This design has several advantages:

- high heat and mass transfer, thus avoiding the creation of hot spots in the bed that are detrimental to reducing NOx emissions;
- high level of in-furnace heat absorption;
- efficient sulphur capture in furnace and therefore lower Ca/S ratio (improved limestone use).

For larger units where four or more cyclones are required the pant-leg configuration is used in boiler design. The most recent advanced coal-fired CFBC power plants installed by Alstom include (PowerClean, 2004; Morin, 2003):

- Can, Turkey: the lignite-fired CFBC power plant has an installed capacity of 2 x 160 MWe and was commissioned in 2006. Both CFBC units have four cyclones, two for each wall, with OMEGA superheaters and reheaters. Effort has been concentrated on the cyclone separation efficiency: the sections, lengths and inclinations of the cyclone inlet ducts have been optimised to improve the segregation at the entrance and the descending fluid velocity has been decreased.
- Red Hills, USA: the lignite-fired power plant is composed of a single steam turbine fed by 2 x 250 MWe CFBC units and was commissioned in 2002. Each CFBC boiler is composed of a single furnace, four fabricated steel cyclones and four fluidised bed heat exchangers (FBHEs), two for bed temperature control and two for reheat steam temperature control. The whole furnace bottom, main gas ducts to cyclones, and the external heat exchangers, are refractory lined.
- Sulcis, Italy: commissioned in 2006, the CFBC power generating unit is designed to burn high-sulphur coal and has a capacity of 350 MWe. Steam conditions of 16.3 MPa/565ºC/580ºC are used which lead to a plant net efficiency of 40% (LHV based). The CFB boiler is composed of high efficiency cyclones and two external FBHEs. The heat from bottom ash is recovered with a dedicated water cooling closed loop and reused in the main cycle improving the plant efficiency. Although the CFB boiler was designed for coal, biomass fuel of up to 15% of heat input has been fed to the boiler since 2007.
- Baima, China: commissioned in 2005, the 1 x 300MWe anthracite-fired power generating unit is the first large-scale CFB demonstration unit in China. The CFB boiler uses pant-leg design with four high efficiency cyclones and four FBHEs. A plant efficiency of 40% is guaranteed.

Based on the operational success of existing large CFBs and experience gained from operation of a large number of PC once-through units, Alstom has developed a conceptual design for the next generation of CFB units with a rating up to 600 MWe, using SC parameters and once-through boiler technology. The main design features are:

- the use of a pant-leg lower furnace design to ensure proper combustion conditions;
- the furnace water walls are a parallel arrangement of all water wall tubes using small tube diameters to keep the mass flow within acceptable limits;
- six steam-cooled high efficiency cyclones of circular shape are used, three cyclones and up to three FBHEs are located on each pant-leg side;
- downstream of the cyclones the flue gases are led to the steam cooled backpass via two overflow ducts. One cyclone outlet duct for each set of three cyclones;
- one tubular air heater for fluidising air, regenerative air heaters for primary and secondary air.

The supercritical steam conditions of up to 27 MPa and 600ºC to 620ºC for the superheater and reheater, respectively, are used.

5.2.3 AE&E Lentjes GmbH

AE&E Lentjes' CFBC system is based on a pant-leg design with FBHE. Both once-though and drum boilers are used in its CFBC system design. To date, more than 100 CFBC units are in operation and the largest CFBC units by AE&E Lentjes are the 2 x 250 MWe lignite-fired Bhavnagar Power Plant in India, which are currently under construction (http://www.aee-lentjes.de/). Details of the features and

Table 12 AE&E Lentjes' coal-/lignite-fired CBFC units

Plant	Size, MWe	Design fuel	Steam cycle, MPa/°C/°C	Start year	Boiler type
Berlin-Moabit (Germany)	100	bituminous coal	19.6/540/540	1989	Benson once through boiler with reheat
Twin Oaks (USA)	2 x 175	lignite	13.8/540/540	1990/91	natural circulation drum boiler
Gardanne (France)	250	lignite, hard coal, petcoke	16.3/565/565	1995	pant-leg design with reheat
Tisova (Czech Republic)	100	lignite	9.4/505	1997	compact CFB, pant-leg design with FBHE
Neyveli (India)	280	lignite	17.3/540/540	2009	pant-leg design with reheat, drum boiler
Morupule (Botswana)	4 x 150	bituminous coal	13.9/540/540	2012	CFB with FBHE
Bhavnagar (India)	250	lignite	17.3/540/540	2013	pant-leg with FBHE

engineering design of AE&E Lentjes CFBC system are not available. The coal- and lignite-fired CFBC power generating units manufactured by AE&E Lentjes, the boiler type and steam conditions used are shown in Table 12.

5.2.4 Babcock & Wilcox

B&W's internal recirculation CFB (IR-CFB) system uses top supported, one- or two-drum boiler designs. A distinguishing feature of the IR-CFB boiler is the two-stage particle separation system that provides improved performance as well as a simplified, cost-effective and efficient boiler design. The primary stage is an impact solids separator located at the furnace exit collecting the bulk of the solids (95–97%) that are then returned to the furnace by gravity. 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 (250ºC to 510ºC) of the boiler convection pass. The main advantages of the two-stage solids separation design include (Maryamchik and Wietzke, 2010):

- 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 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% to 90% less than that used for similar capacity CFB boilers with non-cooled hot cyclones and 40% to 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 turndown ratio (5:1).

Driven by the desire to scale up the utility CFBC units sizes, B&W is developing the design of an in-bed heat exchanger (IBHX). Part of the lower furnace is 'fenced out' by an enclosure providing separation from the surrounding CFB on the sides while keeping the top open. The separating enclosure is partially comprised of the tubes forming the CFB furnace enclosure walls and partially comprised of the designated in-furnace panels. The latter also divides the IBHX into separate sections.

Tube banks of a particular heating surface (such as superheater, reheater or generating surface) are placed in each of these sections. The fluidising air flow rate to each section is controlled separately to maintain a low-velocity bubbling fluidised bed. Bed material fills the IBHX through its open top from the CFB furnace and is discharged back to the CFB from the bottom area of the IBHX. By controlling the discharge rate, the material throughput in the IBHX is controlled. The throughput rate affects the temperature differential between the bed material and heating surface in a given section of an IBHX, thus controlling its heat absorption. Controlling heat transfer in the sections with generating surface allows control of the bed temperature in the CFBC furnace. The IBHX also allows control of the corresponding steam temperature in the sectioned superheater and reheater surfaces (Maryamchik and Wietzke, 2010).

The largest B&W IR-CFB units sold to date are the 2 x 135/150 MWe coal-fired CFBC boilers with reheat at Meenakshi Power Plant (India), which were scheduled to start operation in 2011. The steam conditions used for IR-CFB boilers can be up to 19.7 MPa/560ºC.

5.2.5 Other manufacturers

Kvaerner was market leader regarding BFB technology. Kvaerner's main product was BFB systems but built an almost equal number of CFB boilers. Kvaerner Pulping and Kvaerner Power were acquired by Metso in 2007 and Kvaerner's CFBC technology is now traded under the name CYMIC™.

The CYMIC™ (CYlindricalMulti-Inlet Cyclone) boiler design features an internal hot cyclone without FBHE. The need for a FBHE is absent as the solids are internally circulated by a cyclone, which is integrated in the combustor. The high-efficiency cylindrical cyclones are constructed of membrane walls and light refractory for erosion protection. Membrane cyclones have several benefits such as keeping the amount of refractory used at low level, smaller heat losses and allowing a reduction in size of the other surfaces while participating in heat transfer. As an option, the boiler can feature an integrated bed ash cooler (BAC) together with a loop seal superheater to protect the superheater surface against corrosion and to provide additional heating surface to meet high steam temperature requirements. The BAC design is integrated with the boiler furnace by a water-cooled membrane wall and it is used to cool the bed ash down to 200ºC to minimise heat loss. The superheater can be positioned immersed in the boiler bed material. Metso has a design ready for CFBC units up to 350 MWe in size (Metso, 2011)

In China, the first commercial CFB boiler was manufactured by the former Lurgi Company. Encouraged by its success, intensive R&D in CFB technology started in China in 1982. A large number of small CFBC units were subsequently installed. However, Chinese technology lagged behind the requirements of the power industry to build CFBC boilers over 100 MWe and efficiency above 35%. As a result, China imported foreign CFBC technologies, Foster Wheeler's 100 MWe class CFBC to Dongfang Boiler Works, and 150–300 MWe class to Wuxi Boiler Company; former EVT's 135 MWe class CFBC to Harbin Boiler Works; former CE's 135 MWe CFBC class to Shanghai Boiler Works. At same time, Chinese companies and research institutes independently developed their own reheat CFBC boilers. From 2003 to 2005, three major Chinese boiler manufacturers, Harbin Boiler Works, Dongfang Boiler Works and Shanghai Boiler Works, bought Alstom's CFBC technology for the 300 MWe class. Also, China's Tsinghua University developed a concept design of a 300 MWe CFB boiler that features three cyclones without external heat exchanger (EHE) and a parallel back pass with damper reheat temperature control. By 2008, CFB power generating units with a total capacity of 63,000 MWe were installed, which is more than 10% of total Chinese coal-fired power generation capacity. Among these, around 150 units are in 100 to 150 MWe size and 13 units are in 300 MWe size (Yue and others, 2009; Mao, 2008; Stamatelopoulos and others, 2004). Table 13 shows the 300 MWe CFB boilers installed in China.

Table 13 Recently installed 300 MWe CFBC boilers in China				
Plant	No	Coal	Manufacturer	Start year
Baima	1 x 300	anthracite	Alstom	2006
Qinhuangdao	2 x 300	subbituminous	Dongfang	2006
Honghe	2 x 300	lignite	Harbin	2006
Kaiyuan	2 x 300	lignite	Harbin	2006
Xunjiansi	1 x 300	lignite	Harbin	2006
Mengxi	2 x 300	gangue	Shanghai	2007
Heshuyuan	2 x 300	anthracite	Dongfang	2008
Xialongtan	2 x 300	lignite	Shanghai	2008
Fenyi	1 x 330	lean coal	Harbin	2009
Linhuanzhongli	1 x 300	mix	Harbin	2009

Tsinghua University and the Harbin Boiler Works have recently co-developed a concept design of 600 MWe SC CFBC boiler. This design is based on Alstom's FBC technology featuring pant-leg furnace with six cyclones and six EHEs. Other design features include: combined ignition system both under bed and above bed, vertical tube water wall, bottom ash drained from two side walls through roller type ash coolers (developed in China), and four regenerated air heaters with four sectors. Steam cycles of 24.5 MPa, 571ºC(±5ºC) and 569ºC(±5ºC) for main steam temperature and reheat temperature, respectively, are used for the design (Mao, 2008). China's first 600 MWe SC CFBC demonstration plant at Baima Power Plant was scheduled to start operation late 2012.

5.3 Comparison of PC and CFB

PC combustion uses a proven technology with a very high reliability level. PC boilers have the advantage of being able to accommodate up to 1300 MWe. While the vast majority of existing PC boilers use subcritical steam conditions, newly-constructed supercritical PC boilers are currently being designed to provide steam pressures of 24 to 30 MPa, with main and reheat steam temperatures at 565ºC or higher. To date, several ultra-supercritical (USC) PC boilers are in operation in China, Europe, Japan, South Korea and USA. The economies of scale and advanced steam cycle can result in a significant reduction in total costs as well as lower CO_2 emissions, and therefore large SC and USC PC boilers will be the preferred choice of technology in future.

Compared to conventional PCC, CFBC is a relatively young technology. However, CFBC is commercially proven and has been in reliable electric utility service for the last two to three decades. The capability to burn fuels with characteristics not acceptable to PC boilers is becoming a key issue for CFBC technology selection.

5.3.1 Operational performance

A leading engineering and construction company Black & Veatch (2007) recently carried out detailed evaluations of PC, CFBC and IGCC technologies for power generation from coal. Their full-load performance estimates for PC and CFBC boiler are shown in Table 14. These estimates are based on single units that would be installed at a multiple-unit greenfield site and the same coal is burned in all boilers.

Table 14 Performance estimates for PC and CFBC technology, per unit (Black&Veatch, 2007)

	Subcritical PC	USC PC	CFBC*
Steam condition, MPa/°C/°C	16.7/566/566	25.6/600/610	16.7/566/566
Fuel input, GJ/h	4857	8954	4994
Boiler efficiency (HHV), %	88.9	88.9	87.0
Heat to steam (HHV), GJ/h	4319	7967	4435
Gross single unit output, MWe	550	1054	556
Total auxiliary load, MWe	50	74	59
Net single unit output, MWe	500	980	497
Gross turbine heat rate, MJ/kWh	7.9	7.5	7.9
Net plant efficiency (HHV), %	37.0	39.4	35.9

* 2 x 250 MWe CFBC boilers feed one turbine

Efficiency

While CFBC technology requires more auxiliary power for fluidisation, no pulverisers are required and there is no additional flue gas pressure drop due to FGD and SCR units. The power demand of these components are more or less equal to the power needed for fluidisation and therefore the auxiliary power requirements for the two technologies are relatively similar, with power consumption of CFB being slightly higher. As a result, the net plant efficiency of a CFBC unit may be slightly lower than a PC unit of the same size and with similar steam conditions when the same type of fuel is used. Although CFB can achieve efficiencies comparable to that of PC, the higher endogenous energy use (for fluidisation) limits CFB reaching higher thermal efficiency than PC installations.

Operational flexibility

Both CFBC and PCC technology offer 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 in range of 40%, without supplemental fuel (compared to the minimum load for a PC boiler in the range of 25%). CFBC technology is not well suited for on-off cycling. The bed material is susceptible to hardening if the bed temperature falls below the recommended operating range.

Availability and reliability

The availability and reliability of CFBC technology are considered to be generally equivalent to PC boilers.

Fuel flexibility

A major advantage of a CFBC boiler 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. The greater fuel flexibility of a CFBC boiler relative to a PCC boiler gives its owner the ability to minimise fuel expenses by burning lower quality, lower cost fuels. Additionally, CFBC boilers are able to run on 100% biomass fuel, making the technology attractive in areas that have large amounts of biomass available for a renewable fuel source.

5.3.2 Environmental performance

One of the main advantages of CFBC technology is its low SO_2 and NOx emissions relative to a PC boiler not equipped with flue gas desulphurisation (FGD) and selective catalytic NOx reduction (SCR) systems. The emissions from a CFBC boiler can be further reduced by using a polishing FGD system and selective non-catalytic NOx reduction (SNCR) through injection of ammonia into the upper furnace. CFBC can achieve SO_2 and NOx emission levels similar to those of a PC unit with state-of-the-art FGD and SCR systems. However, the limestone feed rate required is almost twice that of a wet FGD.

A CFBC boiler produces less fly ash but more bottom ash than a PC boiler. The total ash flow for CFBC is larger due to limestone addition and desulphurisation. The bottom ashes from a CFB contain higher SO_3, CaO and $CaSO_4$ than PC-fired ashes.

Water consumption for the two technologies would be essentially identical when drum boilers are used. However, when steam is used for sootblowing, the boiler water make-up requirements may be slightly higher because of the higher sootblowing steam demand of PC boiler technology (Black & Veatch, 2007). A PC power plant will consume more water if a wet FGD system is used for SO_2 emissions control.

5.3.3 Carbon capture

Post-combustion capture technologies for PC applications are expected to be equally suitable for CFB applications. Oxyfuel combustion also is applicable to CFB technology and may have some advantages over PC designs. The oxyfuel combustion process for CFBC is similar to that for PC. However, in oxyfuel CFBC the furnace temperature can be controlled by cooling the circulating solids and lowering the amount of flue gas that has to be recycled. Flowing less gas through the furnace allows its size to be reduced, with associated reductions in capital and operating costs. Also, due to the sulphur captured mainly in the CFB furnace, no FGD is required. Any remaining SO_2 is removed in the cryogenic CO_2 purification stage. Ammonia injection for NOx reduction is eliminated and the NOx is removed in the cryogenic CO_2 purification stage along with the SO_2 (EPRI, 2008).

5.3.4 Costs

In response to some key issues regarding to the Basin Electric Power Cooperative's proposed 368 MWe (net) coal-fired Dry Fork Power Station, Jenkins and Brown (2007) evaluated the available technologies and estimated their costs. As shown in Table 15, their estimates indicated that with

Table 15 Economic analysis for PC and CFB technology options at Dry Fork Station ($ million) (Jenkins and Brown, 2007)

	CFB*	PC†	IGCC‡
Capital cost	1404	1350	1755
First year O&M cost			
Fixed O&M cost	7.5	6.8	9.8
Non-fuel variable cost	11.8	7.7	17.8
Coal coat	10.8	10.4	10.1
Natural gas cost	0	0	11.5
Total first year operating cost	30.1	24.9	49.1
Total first year cost	122.3	113.6	164.4
Net present value (NPV)	2007	1849	2777

* CFB system with w/dry FGD and SNCR
† PC plant with w/dry FGD and SCR
‡ proposed IGCC plant based on two 50% capacity gasifier trains and natural gas back-up fuel with wet or MDEA sulphur removal and without SCR

Table 16 **Economic analysis for PC and CFB technology options** (Black & Veatch, 2007)			
	Subcritical PC	USC PC	CFBC
Net multiple unit output, MWe	2000	1960	1988
Capacity factor, %	92	92	88
EPC cost			
$ million (2006)	3078	2646	3240
$ million (2012)	3568	3067	3756
Unit EPC cost			
$/kW (2006)	1540	1350	1630
$/kW (2012)	2925	2619	3074
O&M costs (2006$)			
Fixed costs, $ million	35.78	27.5	38.8
Fixed costs, $/kW	17.89	14.03	19.54
Variable costs, $ million	45.13	47.5	68.0
Variable costs, $/kWh	2.94	2.86	4.44
O&M costs (2012$)			
Fixed costs, $ million	41.48	31.87	45.05
Fixed costs, $/kW	20.74	16.26	22.66
Variable costs, $ million	54.9	52.3	78.6
Variable costs, $/kWh	3.41	3.31	5.14

42 years of plant economic life, CFBC would require higher capital as well as operating and maintenance (O&M) costs than those of PC technology.

For a large coal-fired power plant with multi-unit and a total installed capacity of 2000 MWe, the capital and O&M costs for CFB and PC technology are shown in Table 16. These estimates are made by Black & Veatch (2007) based on the same assumptions outlined in Section 5.3.1. The cost for CFB technology is based on the use of 250 MWe CFBC boilers. For the required power output, eight CFBC boilers and four 500 MWe steam turbines need to be built compared with four 500 MWe boilers/turbines required for the subcritical PC unit, and two 1000 MWe boilers/turbines for the USC PC unit. The use of multiple boilers to achieve a given steam flow is more costly relative to utilising a single boiler to generate the same steam flow due to the increased physical size of the facility, the incremental ancillary equipment to support additional boilers, and more staff to operate and maintain the additional boilers, as reflected in Table 17. Furthermore, the higher efficiency achieved by the USC PC unit due to the advanced steam cycle used leads to a reduced coal consumption for per unit of electricity generated and therefore lower fuel costs.

With the recent significant advances in scaling-up and the emergence of SC and USC CFBC boilers, the costs of CFBC power plants will be reduced making the technology more competitive. Fan and others (2007) recently analysed the performance and economics of USC CFB power plants. Their estimated costs for USC CFBC power plants are shown in Table 17. The costs for SC PC power plants estimated by Ciferno (2007) are also given in Table 17 for comparison. Comparing the costs of CFBC units in Table 16 and in Table 17, the improvements in economics with increased unit size and advanced steam conditions are clear to see. The data in Table 17 also indicate that CFBC can be very competitive with PCC both technologically and economically. It should be noted that many

Table 17 Comparison of costs of USC CFBC and SC PC power plants

	USC CFBC		SC PC (with wet FGD, low NOx burners and SCR)
Size, MWe	400	800	550
Steam conditions, MPa/ºC/ºC	31/593/593	30/600/620	24/593/593
Net plant efficiency (HHV), %	40.6	41.3	39.1
Coal	Illinois No 6 coal	Illinois No 6 coal	Illinois No 6 coal
Capacity factor, %	85	85	85
Total plant cost:			
$ million (January 2006)	627.8	921.1	
$/kW (January 2006)	1551	1244	1355
Fixed O&M, $ million (January 2006)	19.301	24.8	
Variable O&M, $ million (January 2006)	2.145	2.756	
Total O&M cost, $ million (January 2006)	21.445	27.556	
levelised electricity cost*,$/MWh	52.21	44.08	49.7

* cost of electricity is levelised over 20 years for CFBC plants and over 10 years for PC plants

assumptions are made when evaluating the costs and economics, and these values are indicative rather than absolute. Comparisons of the cost estimates, especially those calculated by different investigators must be done with caution.

In summary, CFBC has emerged as a viable alternative to PC technology for power generation. Commercial CFBC units offer greater fuel diversity than PC units, operate at competitive efficiencies and, when coupled with a polishing SO_2 scrubber and SNCR system, can meet the increasingly stringent emissions standards. There have been continued advances in CFBC technology. Recently, significant developments have been made in scaling-up of CFBC units and in implementing supercritical steam conditions. Today, SC CFBC units up to 800 MWe for bituminous coal or up to 600 MWe for lignite are commercially available. The 600–800 MWe class SC CFB boilers will have performance and economics that are comparable to corresponding PC boilers while offering greater fuel flexibility, especially the ability to burn low heating value opportunity fuels. CFBC technology will play a key role in coal-based power generation in the future, especially in low quality coal and cofiring applications.

6 Summary

It is apparent that for many countries coal must remain an integral component of fuel mix for the foreseeable future. The long-term future of coal-derived energy supplies will have to include the greater use of low rank coal. Despite being geographically dispersed, abundant, and accounting for almost half of the world's coal reserves, lignite/low rank coals find limited use due to their high moisture content and propensity for spontaneous combustion. The use of lignite has been limited mainly to power generation at, or close to, the mining site.

Drying of coal prior to combustion has been proven to improve plant efficiency and reduce CO_2 emissions. A large number of technologies for lignite/coal drying have been developed or are under development and they can be classified into two categories: evaporative drying and non-evaporative dewatering processes. The WTA process, developed by RWE (Germany) and DryFining™, developed in USA, are both evaporative drying processes using fluidised bed coal dryer. The two technologies have recently been successfully demonstrated at industrial scale and are ready to be offered to the commercial market. Several processes based on microwave drying such as Drycol® and CoalTek Process are being tested. These are evaporative processes in which drying takes place at low temperatures and hence minimises degradation of the coal's original thermal and other properties by overheating. The microwave drying processes are still under development. Coldry Process is a coal upgrading technology that removes high moisture content and certain pollutants from lignite and subbituminous coals and transforms the coal into a stable, exportable black coal equivalent product for use by black coal fired power plants. The developer is trying to commercialise the process. Other evaporative drying processes being developed include Windhexe, DevourX mill and the LamiFlo™ system, which are based on high velocity air flow grinding/drying. This type of drying technology utilises high velocity and high pressure air to shatter coal particles so that moisture contained within the coal pore structures can be released. The drying and grinding can be achieved simultaneously.

There are mainly two types of non-evaporative dewatering processes: hydrothermal dewatering (HTD) and mechanical thermal expression (MTE). A number of HTD processes are currently under development. K-Fuel® is a patented technology for low rank coal drying and upgrading. A number of lignites and subbituminous coals have been successfully tested on K-Fuel® process and test burns of K-Fuel® treated coals in several US power generation facilities have also confirmed its technical viability. Its developer is actively commercialising the technology. Continuous Hydrothermal Dewatering (CHTD) has been successfully demonstrated at a pilot scale on coals from various locations. The developer claims that it uses less than 2% of the coal's energy to achieve greater than 60% reduction in water content for Victorian lignites. CHTD can also remove some impurities in the coal and so improve the combustion characteristics of the coal. The Catalytic Hydrothermal Reactor Technology (Cat-HTR) is a catalytic hydrothermal reactor technology designed to convert lignite and biomass into non-conventional crude oil and various upgraded coal products. This technology is under development. The Hot Water Drying process uses high temperature, high pressure to dry a coal in a water medium. This process is still in the early stages of development.

MTE technology combines the use of pressure and temperature to effectively reduce the moisture content of lignite, while requiring significantly lower pressures (<12 MPa) and temperatures (<200ºC). The Australian CRC Lignite worked to develop the MTE process suitable for Victorian lignites. The CRC Lignite found the MTE less expensive than the HTD or WTA process and capable of removing more than 70% of the water from Australian lignite. However, HTD and MET processes generate large volumes of wastewater containing both organic and inorganic maters which is difficult to treat and costly to dispose of. There are many more drying processes that are under development which are not covered in this report.

The majority of existing lignite-fired plants use subcritical PCC technology. Recent advances in boiler and turbine materials have led to the installation of high efficiency SC and USC PCC steam generators. In addition, improvements in process design and engineering not only increase the total plant efficiencies, but also improve the availability, flexibility and environmental performance of the plants and reduce capital and operating costs. The modern design concepts of a pulverised lignite fired power plant apply advanced technologies and improved engineering designs to all parts of the plant.

Careful selection of a milling system can improve lignite combustion in the furnace, reduce the depositions and improve the slagging problems. Most lignite firing utility boilers use tangential firing systems with symmetrical firing configurations. The modern large lignite boilers have furnace dimensions of up to 26 x 26 m in cross-section and 87 m in height. The once-through tower-type (single pass) boiler is used as SC steam generator in BoA technology while a two-pass boiler arrangement is adopted in other modern SC lignite-fired power plants. The optimised thermal designs are crucial to ensure the designed plant efficiency, and reliable and smooth plant operation can be achieved with minimum boiler size. In lignite-fired power plants, the NOx emission limit values can be met by primary measures including: reduction in access air; air staging; vapour separation, fuel compression; flue gas recirculation and low NOx burners. The use of low NOx burners not only significantly reduces the formation of NOx during combustion, it also improves the fuel ignition and flame stability. In a modern lignite combustion plant, especially when lignite of high slagging tendency is burnt, a heating surface cleaning system combining water lances with water-jet blowers that are controlled by an expert system can be used. With this system, the sootblowers are controlled individually to ensure effective heating surface cleaning so the designed heating surface efficiencies are maintained.

The improved system designs and engineering that contribute to increased net efficiency of lignite power plants also include: advanced boiler and turbine materials leading to the new generation of SC/USC steam generators; improved turbine designs resulting in plant operation with high levels of reliability, availability, operational flexibility and increased efficiency; extensive heat transfer systems for optimised waste heat recovery and utilisation.

The considerable variations in the quality of lignite coals impact the design, operation, performance of the plant and hence its capital and operating costs. Research into the applications of the available technologies from which power producers can select the options most suited to preferred coal types, local conditions and compliance requirements are needed.

CFBC is an alternative to pulverised coal combustion for power generation. CFBC is capable of burning a diverse range of fuels and is particularly suited to low grade fuels. The main advantages of the CFBC technology include fuel flexibility and low emissions due to in-bed sulphur capture and low combustion temperature. Continuous technology innovations and improved system designs have led to modern CFBC boilers with enhanced performance, increased efficiency, improved reliability and operational flexibility in a cost effective way. One of the significant advances of CFBC technology over the last ten years has been the increase in the size of CFBC boilers. In addition, the latest CFB boiler designs have adopted once-through supercritical operating conditions to achieve higher plant efficiency. The first 460 MWe SC CFB boiler started operation recently with a net plant efficiency of 43.3% (LHV). Today, SC CFBC units up to 800 MWe for bituminous coal or up to 600 MWe for lignite are commercially available.

The major CFB suppliers include AE&E Lentjes GmbH, Alstom, Babcock & Wilcox, Metso and Foster Wheeler. Foster Wheeler and Alstom are the market leaders.

CFBC can achieve efficiencies comparable to that of PCC. Both CFBC and PC technology offer operational flexibility although the load-following capability of CFB boilers is limited compared to PC boilers. The availability and reliability of CFBC technology are, in general, equivalent to PC boilers. A CFBC boiler has a greater fuel flexibility than a PC boiler and is capable of burning all types of coals, coal wastes and a wide variety of other fuels.

CFBC can achieve SO_2 and NOx emission levels similar to those of a PC unit with state of the art FGD and SCR systems. Post-combustion carbon capture technologies for PC applications are expected to be equally suitable for CFB applications. Oxyfuel combustion is also applicable to CFB technology and may have some advantages over PC designs.

The results from some recent studies indicate that CFBC can be very competitive with PC technology both technologically and economically. The 600–800 MWe class SC CFB boilers will have performance and economics that are comparable to corresponding SC PC boilers while offering greater fuel flexibility. There is no doubt that CFBC technology will play a key role in coal-based power generation in the future, especially in low quality coal and cofiring applications.

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