Utilisation of low rank coals

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Abstract

This report discusses the current status of utilisation of low quality coals worldwide. The largest market for low quality coals is power generation. Power generation using low quality coals is dominated by Pulverised Coal Combustion (PCC) plants. Although the majority of PCC plants uses subcritical technologies, a number of new plants have adopted supercritical steam conditions at large scale. Germany currently leads the way in developing high efficiency large-scale supercritical PCC technology for low rank coals. China and the USA are also developing supercritical PCC technology rapidly for low rank coals. Circulated fluidised bed combustion (CFBC) is, by the nature of its design, very suitable for burning low quality coals for power generation or cogeneration. This technology has been chosen for several repowering projects in Poland and the USA. China now has the largest number of CFBC units, and the 300 MW class CFBC has been rapidly deployed in that country. There is very limited experience with IGCC fuelled by low rank coals, and the major challenges are to increase the plant availability and to lower the capital and operating costs. Coal-to-liquids (CTL) emerges as an important sector in recent years due to concerns revolving security of energy supply and high oil/gas price volatilities. Currently, South Africa has the greatest experience with indirect CTL, while China is rapidly increasing its knowledge base through its large-scale demonstration projects of both direct and indirect CTL. There is also significant interest in CTL in Australia, Indonesia, Japan and the USA. Underground coal gasification (UCG) has the potential for tapping into large, otherwise inaccessible, coal reserves. Australia and South Africa lead the way in developing advanced UGC technologies that build on developments in directional drilling and computer drilling. Drying, cleaning and upgrading of low rank coals are of great importance for increasing the use of low rank coals, as these make the coals cleaner, safer for transport and storage, and more valuable as an exportable fuel. To this end, a number of high efficiency processes are under development in Australia, Germany, Japan and the USA. All these developments in power generation, CTL, UCG, drying and upgrading are likely to ensure a sustainable future for low quality coals.

Abbreviations

ACI	activated carbon injection
ASTM	American Society for Testing and Materials
ASU	air separation unit
BCB	binderless coal briquetting
BFBC	bubbling fluidised bed combustion
B&W	Babcock & Wilcox company
Cat-HTR	catalytic hydrothermal reactor
CCS	carbon capture and storage
CFBC	circulating fluidised bed combustion
CHTD	continuous hydrothermal dewatering
CTL	coal-to-liquids
DCL	direct coal liquefaction
EOR	enhanced oil recovery
EPRI	Electric Power Research Institute (USA)
ESP	electrostatic precipitator
FBC	fluidised bed combustion
FBHE	fluidised bed heat exchanger
FDA	flash dryer absorber
FGD	fluidised gas desulphurisation
HGI	Hardgrove Grindability Index
ICL	indirect coal liquifaction
IBIL	Ignifluid Boiler India Ltd
IDGCC	integrated drying gasification combined cycle
ID	induced draught
IGCC	integrated gasificaion combined cycle
INTREX™	integrated recycle heat exchanger
MTE	mechanical thermal expression
MHI	Mitsubishi Heavy Industry
NDRC	National Development and Reform Comission, People's Republic of China
NETL	National Energy Technology Laboratory, USA
OFA	overfire air
PCC	pulverised coal combustion
PRB	Powder River Basin
rom	run of mine
SC	supercritical
SCR	selective catalytic reduction
SHS	superheated steam
SNCR	selective non-catalytic reduction
SNG	synthetic natural gas
SSD™	superheated steam dryer
SWEPCO	South Western Electric Power Company (USA)
TRIG™	transport integrated gasification technology
UBC®	upgraded brown coal
UCG	underground coal gasification
USC	ultra-supercritical
US DOE	Department of Energy, USA
VOC	volatile organic compound
WTA	fluidised bed drying with internal heat recovery

Contents

1 Introduction

The world's energy consumption is closely correlated with the global economic growth. Extremely rapid economic expansion in many countries outside the OECD, especially in Asia, was the main reason for rapidly accelerated energy demand in recent years. With the world economy slowly recovering from the latest recession, the world GDP will be back on track, growing by an average of 3.2%/y over the period of 2008-30, the same rate as in 1980-2008 (IEA, 2010). The sustained economic growth necessitates the increase in global primary energy demand, which is projected to be 36% by 2035 from the 2008 level in IEA's New Policies Scenario defined in the World Energy Outlook 2010 (IEA, 2010). In this Scenario, fossil fuels maintain a central role in the primary energy mix although their share declines from 81% in 2008 to 74% in 2035. Coal remains the most important fossil fuel after oil; its share in global energy demand will climb from 27% in 2008 to 27.2% in 2020, and then drops to 23% in 2035. Coal's biggest market remains the electricity generation. Globally, coal remains the dominant source of electricity generation in 2035, although its share declines from 41% in 2008 to 32% by 2035. Growth in coal-fired generation is led by the non-OECD countries, where it doubles over the period of 2008-35, while in OECD countries coal-fired generation drops by one-third between now and 2035 (IEA, 2010).

Global coal production in the New Policies Scenario grows from just under 4900 Mtce (million tonnes of coal equivalent) in 2008 to just above 5620 Mtce in 2035. Most of the growth occurs in non-OECD countries. China accounts for half of global coal production by 2035, while Indonesia's output overtakes that of Australia. Coal production in most OECD countries is now expected to decline until 2035; the main exception is Australia, where growth in export demand increase production by 0.6%/y (IEA, 2010). The majority of the world's present production is undertaken on hard coal (defined as coals with a gross calorific value greater than 23.9 GJ/t, ash free but moist basis, mean vitrinite reflectance no less than 0.6) reserves because these coals are currently the major feedstock for power plants, industrial boilers and coking plants. Bituminous coals and anthracites account for around half of the world's proven reserves of 847 Gt, which are adequate to meet projected growth in coal demand through to 2035 (IEA, 2010).

However, the importance of low quality coals has emerged in recent years. A major strategic concern is that the rapid growth in hard coal production has resulted in a sharp fall in the reserves- to-production ratios worldwide. As hard coals are depleting rapidly, the resulting price surge and supply risks are the key challenges facing many coal consuming countries. Moreover, coal market dynamics are also changing; for example, China was a net coal exporter with a peak of 87 Mtce in 2001, but net exports have declined consistently since, and China will become a net coal importer in coming years. This change in market dynamics has forced some coal importers to seek new sources of supply, with subbituminous coal having already begun to gain attention in world markets. Low quality coals thus have an important role to play in maintaining security of coal supply. In addition, since low quality coals are generally produced by surface mining, their production costs are much lower than hard coals that are extracted through underground operations. The lower-cost benefit can be enhanced by desirable coal properties, such as lower sulphur content, of low quality coals. As a result, there is increasing interest in tapping into low quality coal reserves in many parts of the world, particularly where hard coals have been heavily mined. For example, the USA Energy Information Administration, based on results from its National Energy Modelling System, forecast a strong shift from eastern high-rank coals to western low-rank coals from 2008 through to 2035 (EIA, 2010). Moreover, advances in surface mining, labour cost consideration, governmental support and many other factors also contribute to the growing importance of low quality coals.

The term 'low quality coal' is used to refer to a coal that possesses one or more of the following undesirable properties so that their use in coal boilers, gasifiers or other equipments may cause low efficiency or operational difficulties:

- low calorific value;
- high moisture content, which also translates into low calorific value;
- high ash content, related to ash problem and low calorific value;
- low ash fusibility, having high fouling potential;
- high alkali/alkaline content, having high potential for fouling and/or slagging;
- low volatile matter content, related to ignition difficulty and flame stability;
- high sulphur content, implying high SOx emissions and control costs;
- high mercury and nitrogen content with increasing concerns;
- low Hardgrove Grindability Index (HGI), implying high milling power consumption and increased mill wear and hence maintenance costs.

As such, low quality coals include not only low rank coals (sometimes called brown coals) but also low grade coals. Nevertheless, the focus of this report is on brown coals (sometimes termed soft coals) that, according to the International Coal Classification of the Economic Commission for Europe, comprises: (1) subbituminous coal, non-agglomerating coal with a gross calorific value between 17.4 MJ/kg and 23.9 MJ/kg containing more than 31% volatile matter on a dry mineral matter free basis; (2) lignite, non-agglomerating coals with a gross calorific value less than 17.4 MJ/kg and volatile matter greater than 31% on a dry mineral matter free basis. Therefore, the terms 'low quality' and 'low rank' are exchangeable on many occasions in this report.

The economic values of low quality coals are relatively low compared to bituminous coals. The primary reasons are related to their low calorific values (typically less than 16 MJ/kg, LHV) and other undesirable properties that limit their use in conventional coal utilisation equipments. Consequently, despite the low cost, utilisation of low quality coals has been limited to power generation at or close to the mining site. An exception is the subbituminous coal from the Powder River Basin in the USA, which is being transported in large amounts by rail from western mines to eastern markets due to their lower fuel cost and lower sulphur content. Long distance transportation of low quality coals with low calorific value, such as Victorian brown coal in Australia, is uneconomic but upgrading technologies can be applied to these coals to capture distant market opportunities.

The global reserves, production and consumption of low quality coal is discussed in a sister report already published by IEA CCC (Mills, 2010). This report focuses on discussion of application and upgrading of low quality coals. Chapter 2 discusses the use of low quality coal in pulverised coal combustion (PCC) power plants, which is by far the dominant utilisation route for the coal. The impact of coal characteristics, the current status of technology and future development are discussed in some detail. A similar discussion is made in Chapter 3 concerning circulating fluidised bed combustion (CFBC) power plants, which by the nature of the technology is very attractive for consuming low quality coals. Another power generation technology, IGCC (Integrated Gasification Combined Cycle), is discussed in Chapter 4. With only five operating units, there is very limited operational experience with IGCC. Also discussed in Chapter 4 are the coal-to-liquids (CTL) and underground coal gasification (UCG) technologies. One of the major disadvantages of low quality coals is their low calorific value, due either to high moisture content or to high ash content. Drying prior to feeding high moisture coals to either boilers or gasifiers is an effective way to increase the overall conversion process efficiency. The various drying technologies and coal briquetting are introduced in Chapter 5. The emphasis is placed on comparison between various processes in terms of technical maturity and commercial success. For high ash coals, cleaning has to be performed in order to increase the fuel's energy density and reduce the amount ash/slag handling. This is discussed in Chapter 6.

2 Pulverised coal combustion plants

Currently, the largest market for low quality coals is power generation, generally close to the mines from which the coals are extracted. Power generation using low quality coals has been undertaken in three types of coal-fired power plants, namely pulverised coal combustion (PCC) plant, circulating fluidised bed combustion (CFBC) plant, and integrated gasification combined cycle (IGCC) plant. PCC has been the prevailing mode of firing coal for power generation worldwide for more than 75 years and provides the backbone of electricity generation systems in many countries.

In PCC plants, coal is ground to a fine powder and then blown with part of the combustion air through a series of burners. Secondary and tertiary air is introduced subsequently. The burners can be wall-mounted on one side or on opposite sides, or mounted tangentially or in the corners. Combustion takes place at temperatures from 1300ºC to 1700ºC and close to atmospheric pressure. The coal particle residence time in the boiler is typically 2–5 s. The heat released during coal combustion is absorbed by water flowing in water tubes surrounding the boiler furnace to raise steam which subsequently drives a steam turbine to generate electricity (the Rankine cycle). Superheaters and reheaters are commonly used to recover heat from hot flue gas and add it to the steam so as to increase the cycle thermal efficiency. PCC boilers have been built to match steam turbines which have outputs between 50 and 1300 MWe; most recent PCC units are rated at more than 300 MWe due to steam turbine considerations (also to take advantage of economies of scale).

PCC units can be categorised into three types: subcritical, supercritical and ultra-supercritical, depending on the steam conditions entering the steam turbine. Table 1 lists the major differences in steam conditions and materials requirements between subcritical, supercritical and ultra-supercritical PCC technologies. Typically, subcritical units generate steam with conditions of 16.5 MPa/538ºC /538ºC (the superheater outlet pressure/temperature/the reheater outlet temperature) (Kitto and Stultz, 2005). The average efficiency for larger subcritical plants burning good quality coals is in the range of 35–36% (LHV basis), while that of older or smaller units burning poor quality coal can be as low as

Table 1 Comparison of steam conditions and materials requirements between subcritical, supercritical, ultra-supercritical and long-term future PCC boilers (Kitto and Stultz, 2005; Foster Wheeler, 2008)

	Subcritical	Supercritical	Ultra-supercritical	Long-term future
Steam conditions				
Pressure, MPa (final superheater outlet)	12.4*–16.5	24–25	30	35.8
Temperature (final superheater/ reheater outlet)	538/538	540–565/560–595	595–600/600–610	700/720
Materials				
Waterwalls	carbon steel (1/2Cr1/2Mo)	T2, T12 (13 Mo3, 13CrMo44)	T23, HCM2S, 7CrMoVTIB910	HCM12
Superheater	Stainless steel, 9Cr1MoV, SB407-825	T91, T23	347HFG, HR3C, Super 304	Ni-based Alloy
Headers/pipes	9Cr1MoV	P91, P22/P23	NF61, E911, HCM12A	Ni-based Alloy

* for small subcritical units

30% LHV (Kitto and Stultz, 2005). The nominal steam conditions are 24.1 MPa/566ºC/593ºC, typically, for supercritical units. In some supercritical units providing higher cycle efficiencies, steam conditions on the order of 29.6 MPa/579ºC/599ºC and 25.0 MPa/600ºC/610ºC have been used (Kitto and Stultz, 2005). These units are usually referred to as ultra-supercritical PCC units, which typically operate at superheater out temperature around 600ºC. Higher steam conditions result in higher cycle efficiency. For example, the Nordjyllandsværket Unit 3 using a double reheat cycle in Denmark already achieves 47% (LHV basis). In Europe and Japan, the majority of PCC plants constructed since the late 1990s have all been supercritical. Although capital costs of supercritical plants are 2–3% higher than subcritical plants but these costs are offset by lower fuel costs and lower emissions.

PCC dominates power generation using low rank coals. The first PCC unit burning lignite was commissioned in Texas, USA, in the 1920s; the 40 MW at Trinidad operated for more than 20 years before closure by 1940 due to the prevalence of cheaper natural gas fired power plants (Schobert, 1995). In the following decades, advances in PCC power generation have taken place to achieve higher thermal efficiencies while retaining operational flexibility and improving environmental performance. This chapter will discuss the impact of coal characteristics, outline the operational experience gained with low quality coals, and future trend of development.

2.1 The impact of coal characteristics

Coal characteristics can affect coal pulverisation, ignition and combustion of coal particles, ash behaviour, erosion of the refractory lining, pollutant formation and emissions, and the overall boiler availability and efficiency. Low quality coals are known for their high moisture content, aggressive ash characteristics and, in some low grade coals, high sulphur content. These undesirable coal characteristics have strong implications for their use in power generation plants.

The high moisture content of many low rank coals is of the greatest concern in their use in power generation. Larger boilers are needed for high moisture coals because both flue gas mass flow and volume increase considerably with moisture content (another reason is the fouling characteristics of ash in these coals, as discussed later); typically the furnace volume increases by a factor of 2.5. For instance, in Australia, a 500 MWe brown coal boiler has a volume of about 25,000 m^3 compared to 9000 m^3 for an equivalent bituminous boiler (James, 1983). In the USA, the height of a boiler burning high sodium lignite could be 1.30–1.45 times higher than that of a boiler of similar capacity which burns medium volatile bituminous coal (Couch, 1989). Larger boilers require increased capital and maintenance costs for plant components, such as coal and ash handling, and emissions control.

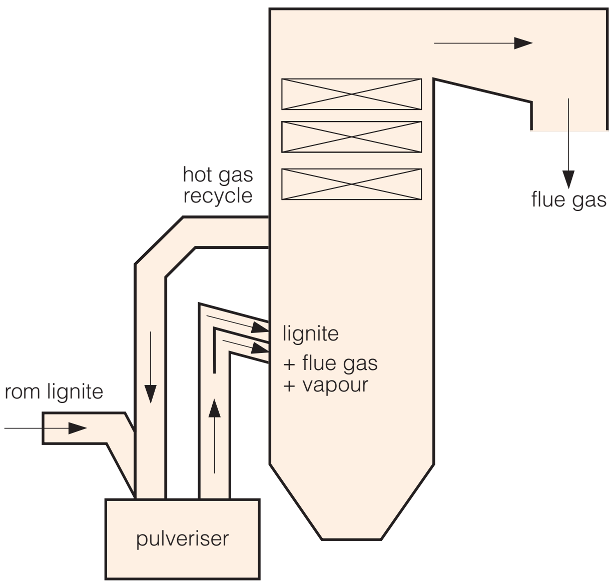

Figure 1 Conventional drying and pulverising (Rousaki and Couch, 2000)

A low rank coal boiler may have a considerably lower thermal efficiency than a bituminous coal boiler. This is because the moisture in the coal must be evaporated before any useful energy can be extracted. It is common to use recirculated flue gases to pre-dry the coal. Recirculation of some 40% of the flue gas is common, which means that the main boiler furnace must be designed to cope with 140% of the mass flow of flue gas. Figure 1 shows the typical drying process in conventional lignite-fired PCC plants. Wet lignite and hot flue gas are fed into the beater-wheel mills. Mechanical pulverisation and drying are carried out in one step. The disadvantage with the conventional drying process is that high temperature flue gas at 900–1000ºC is used whereas drying of moisture occurs at temperature slightly higher than 100ºC. As a result, some 13–20% of the fuel energy is lost in evaporating the moisture (Rousaki and Couch, 2000). To overcome this disadvantage of conventional drying, research efforts have been made to develop more efficient drying technologies. This is discussed in detail in Chapter 5.

Ash formation during combustion can deposit the ash on to the waterwall and superheater/reheater tubes. Heat transfer from hot flue gas to the steam is thus reduced. Deposits may build up to partially block the tube banks, which leads to increased velocity elsewhere thus increasing erosion of the tubes. Large clinkers can form from the build-up of ash deposits on heat transfer tubes, which can weigh several tonnes and can physically distort the tubes. There are also potential risks of large slag deposits falling during operation, which can severely damage the bottom of the boiler. In addition, corrosion may occur underneath developing ash deposits. Sulphur and alkalis in the coal have been associated with corrosion, and the problem becomes more severe as superheat temperatures increase. Both erosion and corrosion rates rise with increasing tube metal temperature. For coals with high sulphur and/or chlorine content, supercritical steam temperatures may require use of newer steels with high corrosion resistance. Materials development will be discussed briefly later.

The deposition characteristics of ash affect the size of the boiler and consequently the heat transfer surface. Low quality coals prone to slagging or fouling need to be fired in larger boilers where more of the heat transfer takes place through the boiler water wall and the temperature is more controllable at the upper convective part of the furnace. This is another reason why many boilers burning low rank coals are larger than a hard coal fired boiler of similar output. High concentrations of alkali metals have been linked to fouling and slagging of coal because alkali metals influence the ash softening and melting behaviours. Experiences in power plants show that by keeping the waterwall clear of the highly reflective slag formed from the low rank coal ash, increases in furnace exit gas temperature can be avoided and the fouling of the superheater reduced. Superheater fouling is managed by increased frequency of sootblowing, but boilers with finned economisers may still have fouling problems. Much of the knowledge about ash fouling/slagging is based on experience due to the complex deposition mechanisms involved (Couch, 2006). A variety of indices are used to estimate the slagging/fouling characteristics of coal ash, although they have limited use for low quality coals or coal blends (Dong, 2010). A combination of laboratory tests, such as computer- controlled electron microscopy, and mathematical modelling is capable of predicting the slagging/fouling tendency of a blend relative to a design coal.

Zygarlicke (1999) described a 425 MWe unit burning a North Dakota lignite, which had experienced severe slagging and fouling problems. A plan was implemented to use mine-planning, coal-blending and boiler operation strategies. A historical review of the lignite mine and of the boiler operation revealed several locations in the mine where coal was associated with severe slagging- and fouling-related deratings and outages. Samples extracted from these locations were analysed and the results were collated against those of samples from other parts of the mine. A boiler inspection and evaluation programme was initiated to provide up-to-date information on deposition severity and the impacts on boiler operation. Indices covering slagging and both low- and high-temperature fouling for these coal samples were developed. These were used for assessing coal quality and developing coal blending strategies. Furthermore, these indices were also related to standard ASTM analysis results (because these data are less expensive to acquire). Daily analyses of coal entering the plant were used to calculate fouling indices which were then compared to boiler performance. This was related directly to the severity of boiler tube fouling and of the burner operation. The cleanliness of the furnace wall and the superheater/reheater regions were regularly recorded; deposit samples were also collected from the reheater for analysis. In addition, a correlation between ash deposition prediction indices, sootblower control, gas attemperation, flue gas recirculation and flue/oxygen ratios was established to facilitate minimising ash slagging/fouling. As a result, it was possible to extend the period between cleaning shut-downs by some 2–3 weeks, with significant savings in costs. Another outcome is the 'smart' mining which forewarns the plant when a known high-fouling seam of coal is being fed to the boiler.

Sulphur dioxide is one of the major atmospheric pollutants emitted from coal-fired power stations. International agreements, such as the UN 1999 Protocol to Abate Acidification, Eutrophication and Ground-level Ozone and the EU Directive on the Limitation of Emissions from Large Combustion Plants, and national emissions standards in many parts of the world necessitate the reduction of sulphur emissions from coal-fired power plants. These regional and national emission standards/limit values for major air pollutants from coal combustion plants are detailed in the Emissions Standards Database compiled by the IEA Clean Coal Centre (IEA CCC, 2010). It is noted that emissions standards have been revised over time and have become more stringent. As a response, power utilities either switched to low sulphur content coals and/or installed SO_2 control equipment. For instance, many power plants in the central-eastern USA are switching from traditional feedstock, the Interior and Appalachian coals, to low sulphur Powder River Basin (PRB) subbituminous coals. The change in feedstock has many technical implications regarding the coal combustion behaviour in the furnace as well as ash slagging/fouling characteristics. There are various means for controlling SO_2 emissions from coal combustion. Flue gas desulphurisation (FGD) is an effective measure and is being applied widely in coal-fired power plants worldwide. Currently, most FGD installations use calcium-based sorbents and the wet limestone scrubbing is most widely used. All the supercritical plants built in the 1990s have FGD equipment and SO_2 removal efficiencies of 95% or better are common. Non-calcium desulphurisation technologies are also available or being developed for SO_2 control in regions where there are limited resources of water or lime/limestone. These technologies have been reviewed in an IEA CCC report (Zhu, 2010). The calorific value of the coal has an important effect on the sulphur emissions. Low calorific value coals result in higher emissions as more fuel has to be burned for the same output. For example, a 14.5 MJ/kg coal with 1% sulphur emits about 4000 mg/m^3 of SO_2, double that if the heating value is 29 MJ/kg for the same electrical output (Rousaki and Couch, 2000). This implies that low quality coal fired power plants may have an increased FGD requirement.

Coal reactivity affects carbon burnout and is therefore an important factor for all PCC applications. Many low rank coals tend to have high reactivities and this is an advantage. Since high reactivity coals have different combustion behaviour, the boiler design will be different compared to that for hard coals. An example is the residence time needed for coal particles which may affect the furnace height or burner arrangement. Coal reactivity also determines the fineness of grind required and hence the pulveriser capacity. Coal grindability is another issue for PCC as it affects the pulveriser system design and performance. Low rank coals often have a low Hardgrove Grindability Index (HGI) which means they are hard to pulverise.

2.2 Current status of technology

Currently, subcritical PCC units account for the majority of current low rank coal based power generation. The subcritical technology for 500–600 MWe output is commercially mature and widely deployed in many countries; units with smaller capacity (150–350 MW) exist in some countries such as Greece, Bulgaria, India and Thailand (Couch, 1989). Some operational problems mainly associated with slagging, fouling and erosion are still encountered in subcritical PCC plants. This is largely due to the difficulties in predicting properties of low rank coals and insufficient understanding of their impact on the plant operational performance. Commercial PCC has been evolving over time from subcritical to supercritical steam conditions, as shown in Figure 2a. Started in 1950s in the USA, the technological development has been advanced considerably in Japan, western Europe and China over the past two decades, with steam conditions being pushed increasingly to higher levels as shown in Figure 2b. At the end of 2007 there were more than 112 units in operation in China, more than 60 units in Europe, some 23 in Japan, some 22 units in South Korea, and about 120 SC PCC units in the USA (estimates based on Dillon and others, 2007; Minchener, 2010). Hundreds more units will be added over the next few years as China is now relentlessly increasing its coal-fuelled power

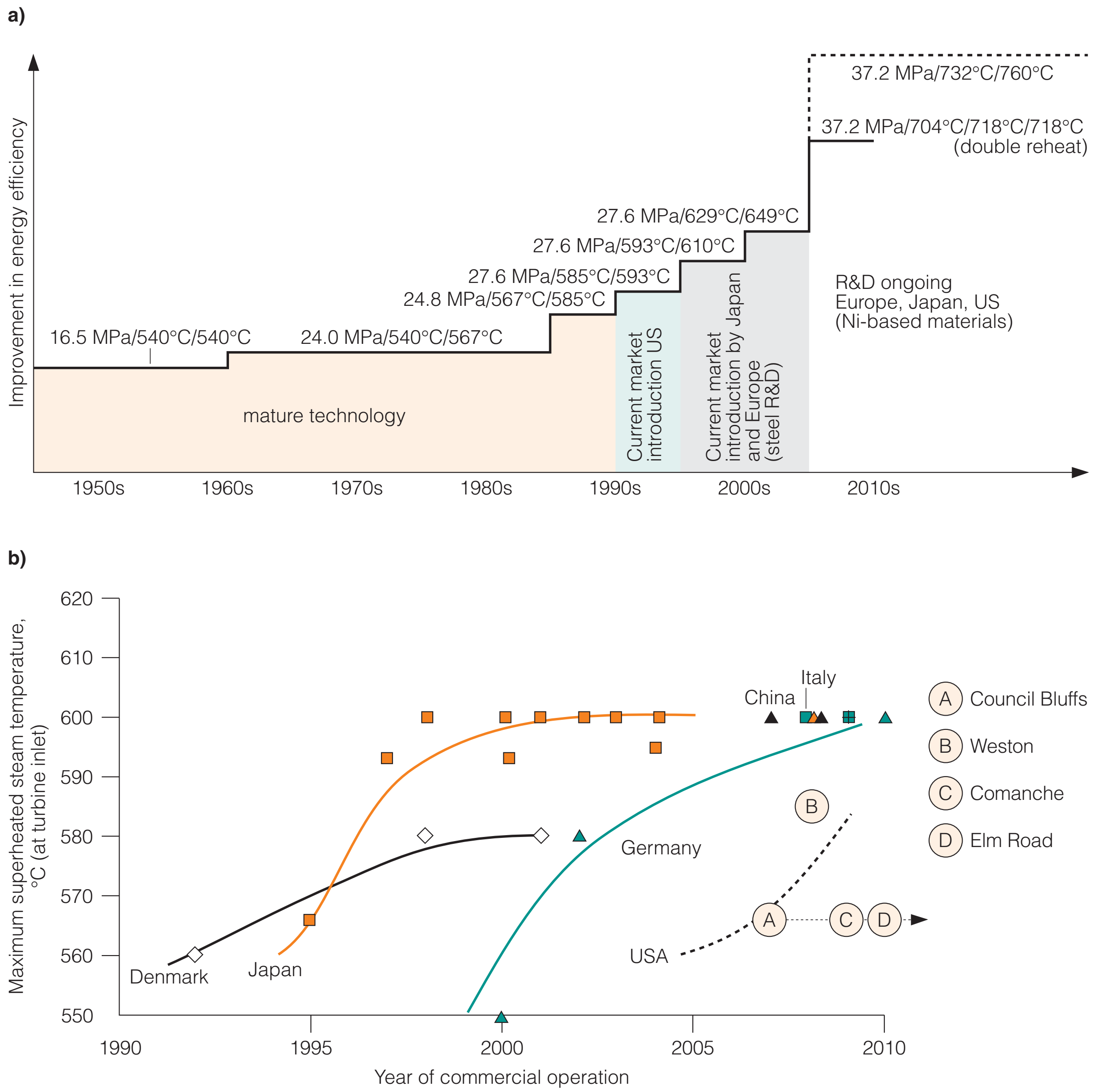

Figure 2 **(a) The progress of supercritical PCC technology over time** (Dalton, 2010; **(b) The trend of ultra-supercritical PCC technology development between 1990 and 2010** (Dillon and others, 2007)

generation capacity (Minchener, 2010). Some of these SC/USC units, except for those in Japan and South Korea that burn imported hard coals, are fuelled by lignites or subbituminous coals.

2.2.1 USA

The past decade has seen confidence, and interest, in supercritical PCC being renewed in the USA after the technology fell out of favour since 1970s due to poor performance of early-built units (with steam conditions typically of 24 MPa/540°C/540°C (567°C)). Part of the reason is that the commercial emphasis in the USA has shifted strongly towards combustion efficiency in order to reduce unit costs and to help meet more stringent emissions legislation and increasing electricity demand. All these strongly favour the development and installation of supercritical PCC units. Plants built during this period include the Walter Scott Jr Energy Center (formerly Council Bluffs) Unit 4 (790 MW, burning low sulphur PRB subbituminous coal, commissioned in 2007) and Luminant's Oak Grove Plant (2 x 796 MW (net), burning lignite, commissioned in 2009 (unit 1) and 2010 (unit 2)). As of mid-2007, about 36 supercritical plants had been announced for construction beginning in 2006-14 despite a few highly publicised cancellations; about 9 GW of coal-fired supercritical PCC units were under construction in the USA in 2008 (Parkes and others, 2008). A close examination of the size of these planned units shows that about two-thirds of announced plants are expected to have net output greater than 680 MW, which suggested a trend in PCC output capacity towards larger units of 750 MW (net) and above. Approximately 70% of the planned supercritical PCC units will operate on subbituminous coal and about 25% will use bituminous coals, and currently only four units planned will be lignite-fired (Dillon and others, 2007). Advanced supercritical steam conditions (27.6 MPa/585ºC/593ºC) are currently being introduced in the USA market. EPRI's CoalFleet research has suggested that supercritical technology will be the standard for new USA PC units by the early 2010s (Dillon and others, 2007).

At present, there are approximately 120 supercritical PCC units but no ultra-supercritical units in operation in the USA. A few recently built units are described as follows.

Walter Scott Jr Energy Centre Unit 4

The 790 MW supercritical coal-fired PCC unit (formerly known as Council Bluffs Unit 4) was built by MidAmerican Energy at the Walter Scott Jr Energy Center, Iowa. Similar to the three existing PCC units, Unit 4 burns PRB subbituminous coal. This unit doubled the total output of the site to 1600 MW, making it the largest electricity producer in Iowa. This US$1.2 billion investment was the first new supercritical coal plant built in the USA in more than 15 years. The plant came into service on 1 June 2007; this is widely regarded as signalling the beginning of a revival of North American interest in supercritical technology as more utilities try to diversify from gas and use more coal.

Unit 4 derived its design from a 1050 MW unit that Hitachi supplied for Tokyo Electric Power Company's Hitachi Naka plant. The supercritical boiler was supplied by Hitachi America Ltd, and has steam conditions of 25.3 MPa/569ºC/595ºC and delivers 2.495 million kg/h of steam. This Benson sliding-pressure boiler includes a spiral-wound waterwall furnace and a double backpass convection section, the first of its kind in the USA. The tubes are rifled to increase heat transfer by suppressing departure from nucleate boiling in the subcritical-pressure region and pseudo-film boiling in the supercritical-pressure region. The lower part of the furnace has an opposed firing system. The boiler design minimises imbalances of fluid temperatures at the furnace waterwall tube outlet, thus improving reliability. The steam turbine was also manufactured by Hitachi, which is a tandem-compound, four-flow, single-shaft, 3600 rpm machine with 40 inch (101.6 cm) last-stage titanium blades. This unit features sliding-pressure operation of the boiler, which is controlled as a function of steam turbine power with the turbine governing valves wide open. This minimises throttling losses and allows the steam pressure at the turbine inlet to change to maintain flow at a constant volume. Sliding-pressure operation also improves the thermal efficiency of the steam turbine at partial loads by decreasing thermodynamic losses.

The unit also incorporates state-of-the-art air pollution controls to keep NOx, SO_2, mercury and particulates in check. These include low NOx burners, separated overfire air system and SCR for NOx reduction, three dry lime-injected spray dryer-absorbers for SOx reduction, activated carbon injection for mercury capture and a baghouse that removes more that 99% of particulates. Since the PRB coal contains high calcium content, the ash sticks easily and poisons the catalyst. A Hitachi plate-type catalyst, with a higher resistance to dust plugging, has been modified to achieve higher durability in PRB-fired flue gas.

Comanche Unit 3

The Comanche Unit 3 near Pueblo, Colorado, is Xcel Energy's first new coal-fired electric generating unit in nearly 30 years. This US$1.3 billion, 750 MW, supercritical PCC unit adds to two existing units that generate about 660 MW. After the Comanche 3 went into full service in July 2010, the

Comanche Station provides nearly 1400 MW of electricity, sufficient for about one third of Colorado's communities. Alstom designed, supplied, erected and commissioned the supercritical boiler for the unit, while Mitsubishi Heavy Industries (MHI) supplied the supercritical steam turbine.

All three units at Comanche station burn low-sulphur PRB subbituminous coal from Wyoming and feature advanced emission controls. All three units now have low-NOx burners (Alstom's TFS 2000 firing system), and Unit 3 is also equipped with a SCR system. Baghouses and lime-spray dryer-absorbers are installed on all units to control particulates and SO_2 emissions respectively. Activated carbon injection is installed, which makes Comanche Station the first plant in Colorado to control mercury emissions. As a result of the Station's environmental improvements, the overall emissions of SO_2 and NOx are effectively reduced by 65% and 30% respectively, despite the doubling in overall electricity generation. To address the drought conditions in Colorado in recent years, Comanche Unit 3 is also equipped with a system that uses both water and air for cooling. This reduces the unit's water use by about half compared to wet-cooling only.

Oak Grove Plant

The two 800 MW Oak Grove units are located in Robertson County about 130 miles north of Houston near Franklin, Texas, and owned by Luminant, the largest electricity generator and lignite coal miner in Texas. Luminant now produces about 20 Mt/y of lignite and is expected to increase that output to 33 Mt/y to meet the fuel needs of new power generation plants. The Oak Grove units are two of the three units remaining out of the initially planned 11 coal-fired units by TXU (the predecessor of Luminant) after the 'green takeover' by a group of private equity investors which scaled back the initial plan due to a storm of opposition from environmental groups. The two units were brought into service in 2010 and burn lignite extracted from the nearby Kosse mine that is able to produce 9.2 Mt/y of lignite and to fuel the two units for more than 40 years. Typically, the Koss lignite has a heating value of 15.9 MJ/kg, 33% moisture, 12% ash, and <1% sulphur. The Oak Grove units represent the latest installation of PCC burning low rank coal in the USA.

The key performance parameters of the two Oak Grove supercritical units are shown in Table 2. It is noted that the steam conditions (24.4 MPa/538ºC/538ºC) are of the same order as those for old supercritical plants built in the 1960s and 1970s. This is because the two units use some 'old' expensive, long-lead equipment including the boilers which had already been purchased in the late 1970s when TXU had approved construction of two lignite-fired power plants, called Forest Grove and Twin Oaks. These two construction plans were suspended following a sudden drop in electricity demand in Texas. All the delivered equipment was carefully preserved and eventually used for the two units at Oka Grove. The boiler of Unit 1 was supplied by Combustion Engineering (now Alstom Power) which uses a tilting corner-fired design, while unit 2 employs a wall-fired boiler fabricated by Babcock & Wilcox Company (B&W).

The Oak Grove plant is also noted for its air emissions control systems. The original boiler design was upgraded with low NOx burners and overfire air system and then retrofitted with an SCR system in order to comply with more stringent NOx emission standards that were not required 30 years ago. Oak Grove is the first plant in the USA that has installed SCR on a 100% lignite-fired power plant. Another first for lignite-fired US plants is the activated carbon injection (ACI) system installed in accordance with Luminant's fleetwide programme to reduce mercury emissions from its coal-fired plants. The plant also has a wet FGD system to control SO_2 and a modern baghouse to meet tight particulate limits. The plant features another modern development, a suite of continuous air emissions monitors, which measure and log NOx, SO_2, ammonia slip, CO, and particulate matter. A continuous mercury monitor also was added to each unit to monitor performance of the ACI system. The plant has an advanced digital control system, used particularly in the balance of the plant and the electrical switchgear (Peltier, 2010).

Table 2 The key parameters of the two supercritical units at the Oak Grove power plant (Peltier, 2010)		
Parameter		Unit 1 and Unit 2
Net unit output		796 MW
Turbine throttle conditions		Main stream: 24.4 MPa/538°C Reheat stream: 4.7 MPa/538°C
Fuel		Lignites from the Kosse Mine, typically, 15.9 MJ/kg, 33% moisture, 12% ash, and <1% sulphur
Emission	NOx	0.08 lb/million Btu (40 mg/MJ)
	SO_2	0.192 lb/million Btu (96 mg/MJ)
	CO	0.34 lb/million Btu (170 mg/MJ)
	PM_{10}	0.015 lb/million Btu (7.5 mg/MJ)
	Mercury	Activated carbon injection, up to a rate of 9.2 lb/thousand Btu (4.6 mg/MJ)
Boiler	Type	Supercritical
	Steam pressure	25.7 MPa
	Steam temperature	543°C/541°C
	Maximum continuous rating	5,740,000 lb/h (2.6 Mt/h)
Turbine	Rating	870 MW
	Type	Single-flow high-pressure turbine, double-flow intermediate-pressure (reheat) turbine, four-flow low-pressure condensing turbines
	Ratational speed	36 rpm
	Condenser Vacuum	2.26 inches HgA (7653 Pa)
	Feedwater heaters	Six stages of feedwater heating, including deaerator
Generator	Voltage	24 kV
	Capacity	955 MVA@0.91 power factor
Boiler feed pump configure ration		Two 50%-sized pumps, steam turbine-driven
Water pre-treatment system		Well water for service water and plant feed water make-up

John W Turk Jr ultra-supercritical unit

This US$1.7 billion 600 MW unit of SWEPCO (Southwestern Electric Power Company) is currently under construction in Hemstead County, Arkansas. It represents the only coal-fired PCC installation using USC steam conditions in the USA and the only survivor of the initially planned four USC units in the country. The Turk Plant is designed to burn low sulphur PRB subbituminous coal. B&W has been chosen to design, fabricate, supply and install the ultra-supercritical spirally-wound universal-pressure waterwall boiler, the SCR system, the dry flue gas desulphurisation system, pulse jet fabric filters and associated auxiliary equipments. Other emissions control features include low NOx burners with close-coupled overfire air and activated carbon injection for mercury reduction. This plant is estimated to come online in late 2012. However, oppositions from local environmental groups have led to three court rulings against SWEPC's construction of the coal plant. In June 2010, SWEPCO chose to convert this power plant to a merchant plant in order to avoid the need for Arkansas approval for the plant. This move meant that SWEPCO would sell the electricity to its customers in Texas and Louisiana, but none to customers in Arkansas. Although SWEPCO and its partners have already committed significant amounts of funds into this project, there is still uncertainty whether a permanent court injunction will be imposed on the entire project. As a result, the construction process of the plant has been delayed.

According to US DOE's National Energy Technology Laboratory, as of January 2010 there are 4.3 GW of subbituminous coal-fired capacity and 2.7 GW of lignite-fired capacity proposed in the USA. The Lignite Energy Council of North Dakota, through its Lignite Vision 21 project, is also funding studies to select an advanced technology for clean and efficient power generation for a designated new 500 MW generation plant (Lignite Vision 21, 2010).

2.2.2 Australia

Coal, with total proven reserves of 76.2 Gt, is of vital importance to Australia, both as a major export and as a domestic source of energy. The reserves comprise 36.8 Gt of anthracite and bituminous coal, 2.1 Gt of subbituminous coal, and 37.4 Gt of lignite (Mills, 2011). The majority of good quality black coal reserves is located in New South Wales and Queensland, while lignite (brown coal) reserves are concentrated in Victoria and South Australia. In 2008, 325 Mt of hard coal were produced, and 72.4 Mt of brown coal. More than three quarters of hard coal output is exported. Most brown coal is mined in Victoria with about 3.8 Mt coming from operations in South Australia. The Australian power generation sector comprises 21 GW of black coal-fired capacity plus 6.6 GW based on low rank coals that accounts for a third of the country's total electricity output (Mills, 2011). Victoria has 6555 MW of lignite-fired generating capacity, and South Australia, 770 MW (Mills, 2011).

The Latrobe Valley Energy Industry operates a number of major brown coal-fired power stations in Victoria. These include GEAC's Loy Yang A (2200 MW), International Power's Loy Yang B (1050 MW), International Power's Hazelwood Power (1600 MW), and TRUenergy Yallourn (1480 MW). Together, these stations supply more than 85% of Victoria's electricity demand. Of these, the Loy Yang station is the largest, generating around a third of the state's electricity. Accordingly, its attendant opencast mine is also the largest in the country. Loy Yang B is Victoria's newest base load power station, producing 17% of the state's power needs.

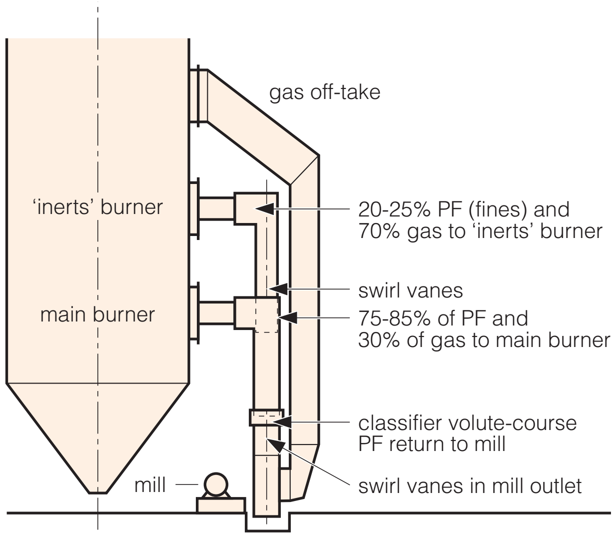

Figure 3 Typical separation firing system developed for Victoria Brown Coal (Allardice and Young, 2003)

In Australia, all brown coal fired PCC units are based on conventional subcritical PCC technology, which was introduced to Victoria from Germany at Yallourn C and D stations in the 1950s. A further development, known as separation firing, as illustrated in Figure 3, is required because of the high moisture content of Yallourn brown coal (66%). By use of a centrifugal swirl device, a fuel rich steam (up to 80% of the feed coal) is separated and fed to the main burners to achieve a stable flame. The remaining 20% of the finer coal is carried in the bulk of the recycled flue gas and evaporated coal moisture vapour, then over-fired through the 'inerts' burners higher in the furnace. This modified combustion technology has been applied to subsequent stations at Yallourn and Loy Yang. Hazelwood, burning a lower moisture content

(60%) Morwell coal with greater ease of ignition, does not require separation firing. Since the 1950s, brown coal units have increased in size from 20 MW to 500 MW, however, there has been little change to the basic technology. The high capital cost of conventional brown coal plants relative to black coal plants, coupled with their higher CO_2 emissions per unit of energy output, militates against further units of this design being built in Victoria. The future for brown coal power will depend on a new generation of more efficient conversion technologies and/or pre-drying processes. A forerunner of these is HRL's IDGCC process; a detailed introduction to this technology is given in Chapter 5.

Supercritical PCC has been installed in Queensland over the last decade; plants include the Callide C, Tarong North, Millmerran and most recently Kogan Creek, with a total generating capacity close to 2900 MW. However, all these supercritical units except Millmerran (described below) operate on good quality hard coals mined in Queensland. The 750 MW Kogan Creek represents the largest single supercritical PCC unit installed in Australia. The average steam conditions of these supercritical units are of the order of 24.2–25.1 MPa/540–566ºC /560–566ºC (Appleyard, 2005). There have reportedly been no additional reliability issues associated with the use of supercritical boilers at these plants so far. Tarong North even boasted an availability of more than 93% in 2003.

Millmerran

The Millmerran is a minemouth power station located in Queensland, Australia. The plant fires low sulphur low grade coal (35% ash content) in two 420 MWe supercritical units operating at 24.1 MPa/566ºC/593ºC (Fernando, 2004). The two supercritical boilers were supplied by B&W and have been designed to handle coals with high mineral content. The design features a two-pass arrangement that has tube spacing sufficient to accommodate the abrasiveness of the fuel ash. The boiler has a spiral wound furnace with ribbed waterwall tubes, and an integral boiler start-up system with two steam separators feeding into a single collection tank. There are two primary air, forced draught and induced draught fans and a single regenerative air heater. Low NOx burners are used, but desulphurisation scrubbers are not required (Appleyard, 2005). Five vertical roll-and-race mills feed 218 t/h of fuel to the burners. The tandem compound, single reheat, condensing turbines with 40% bypass steam flow were supplied by Ansaldo and each connected with a 3000 rpm generator. The plant uses forced draught air-cooling technology to condense the steam which results in around 90% less cooling water use than conventional water-cooled plants. The make-up water is mostly from tertiary treated effluent sourced from the local community and processed by a project-built pipeline and treatment plant (Appleyard, 2005). Fly ash is mixed with water to minimise dust and trucked back to the mine for backfill.

The A$944 million plant is owned by Millmerran Power Partners (the majority partner is InterGen, a Shell-Bechtel joint ventrue), Marubeni Corp, GE Structured Finance, EIF, Tohoku Electric Power Co Inc and the Chinese Huaneng group. Its first unit was brought into service in September 2002, and the second unit in February 2003. The plant has been operating satisfactorily though there have been some problems with the baghouse due largely to the poor quality of the ash (Fernando, 2004).

2.2.3 China

China has vast reserves of low rank coals. Despite some uncertainty remaining with the country's coal reserves data, subbituminous coal (33.7 Gt) and lignite (18.6 Gt) are generally estimated to account for about 46% of China's total proven coal reserves (BP, 2010). Most of these low rank coals are in more remote areas such as the northeastern provinces (with relatively lower moisture content), Inner Mongolia and Yunan Province in southwestern China (with higher moisture content). Around half of China's coal output is used for power generation, and coal-fired power plants produce nearly three quarters of the country's electricity. The vast majority of coal used for power generation is bituminous; lignite contributes only about 5%, thus its overall impact on power generation is limited (Mills, 2010). However, lignite remains of local importance in some regions, and in recent years, its level of use has been increasing, particularly in Inner Mongolia and the northeastern provinces.

Lignite (brown coal) is currently used in all major types of power plant in China. The Yuanbaoshan Unit 1 (300 MW) in Inner Mongolia is China's first lignite-fired PCC unit that came online in 1978. By the end of 2010, it is expected that more than 15 GW of lignite-fired plant with output capacity greater than 200 MW will have been developed in China (Asia Pacific Partnership, 2008). The majority of lignite-fired plants use the conventional subcritical PCC technology. Most of these vary in size between 100 to 600 MW, with the biggest plants consuming about 2 Mt/y of lignite (Mills, 2010). As a result of effective technology transfer from OECD technology developers via joint ventures or production licensing, supercritical and ultra-supercritical PCC technology has undergone rapid development and deployment in China over the past decade (Minchener, 2010). At the end of 2007, there were 112 SC/USC units already in operation and more than 167 under construction, more than 120 ordered (Minchener, 2010). This rapid uptake is also reflected in new lignite-fired power generation units being introduced in recent years. As of 2008, there were more than ten sets of 600 MW supercritical lignite-fired PCC units under construction (Asia Pacific Partnership, 2008). This section describes two large subcritical PCC plants and two of the latest supercritical PCC plants.

Yuanbaoshan power station

Yuanbaoshan power station, located in Inner Mongolia and owned by China Power Investment Corporation, is currently the largest lignite-fuelled power plant in China. It has four subcritical units with total net output capacity of 2100 MW. Unit 1 (300 MW) is China's first large lignite-fired PCC unit and came online in 1978. It has a corner-fired tower boiler with a fan mill system, which was supplied by Sulzer in Switzerland. Its steam turbine and generator were supplied by CEM in France. Unit 2 has a similar design to Unit 1, however this larger unit (600 MW) had encountered severe slagging problems due to inappropriate furnace design. This unit was unable to operate at full load between 1985 and 2000 before a complete redesign took place. Units 3 and 4 were both manufactured in China, by Harbin Boiler Co Ltd, and both have a 600 MW output. Their design incorporated improvements based on lessons learned from Unit 2. Since Unit 3 was brought into service in 1998 and Unit 4 in 2007, they have achieved good availability and operational performance.

Yangzonghai thermal power plant

Yangzonghai is a large minemouth power plant owned by China Guodian Group and located near Kunming in Yunan province. This plant has four subcritical units with total output capacity of 1000 MW which burn high moisture Yunan lignite. Unit 1 and Unit 2, each with an output capacity of 200 MW, were built in the 1990s, and each has a large boiler capacity of 670 t/h to accommodate the high moisture content of the fuel. Unit 1 uses the fan mill system with hot air/flue gas direct drying and has corner-fired burners with a separation-firing configuration, while Unit 2 does not have the separation-firing burners arrangement and its mill output is coarser than that of Unit 1. As a result, Unit 2's net output is short of design value. Nevertheless, its performance is acceptable with no severe slagging on the waterwalls and average boiler efficiency of 87-89%. In 2005 Yangzonghai started its 'Phase III' construction of 2x300 MW PCC units with all three major plant components supplied by domestic manufacturers. The boilers were supplied by Wuhan Boiler Group, while the steam turbines were manufactured by the Dongfang Electric Corporation. Desulphurisation systems were also installed on the two new units and retrofitted to the old units in 2006 and 2007. The new units went online in November 2007.

Huaneng Jiutai power plant

The Jiutai power plant is located in the northeastern Jilin province and owned by the China Huaneng Group. Its planned capacity comprises four 660 MW supercritical lignite-fired PCC units, which are being built in two consecutive phases. The first 660 MW unit costing RMB 5.2 billion went online in October 2009. It is of Chinese design (tower boiler type with fan mill systems). The supercritical boiler was supplied by Harbin Boiler Co Ltd, one of the largest utility boiler manufacturers in China, which now offers 300–360 MW class subcritical and 600–660 MW class subcritical/ supercritical/ ultra-supercritical PCC boilers. Harbin Boiler is also currently leading a consortium to develop China's own lignite-fired 1000 MW ultra-supercritical PCC boiler. This development project is funded by the Chinese government's '863 programme' and went through the appraisal process by the

Ministry of Science and Technology in May 2010. Harbin Boiler is expected to offer the 1000 MW class ultra-supercritical boiler for lignite power plants in the next few years.

Liaoning Qinghe power plant

This power plant is located in the northeastern Liaoning province with a total output capacity of 1200 MW. After being incorporated into the China Power Investment Corporation in 2003, four 100 MW small units were planned to be replaced with a large advanced unit in order to comply with the ‘large substitute for small’ requirement by China’s National Development and Reform Council (Minchener, 2010). This led to the construction of a 600 MW supercritical PCC unit that came online in March 2010, representing the latest installed lignite-fired supercritical PCC unit. During full-load test operation, it performance was reported to be high. The success of this plant, together with that of the Huangneng Jiutai Unit 1, is likely to stimulate the development of similar projects in northeastern China.

2.2.4 Europe

Europe is the third largest coal consumer after China and the USA. In 2008, EU-27 coal supply amounted to 820 Mt, comprising 153 Mt of indigenous hard coal production, 230 Mt of imported hard coal, and 441 Mt of indigenous lignite. If the lignite output from other non-EU countries such as Turkey and Serbia is included, the European lignite total amounts to around 550 Mt (Mills, 2010). Lignite is therefore the most important indigenous coal resource in Europe. The biggest individual European producers of lignite and/or subbituminous coals are Germany, Turkey, Greece, Poland, the Czech Republic, Serbia, Romania, Bulgaria and Hungary. There are also small amounts produced in the Balkan Peninsula. The reserves, production and consumption of coal in respective European countries are reviewed in a sister IEA CCC report (Mills, 2010).

Europe, together with Japan, has taken the lead in developing coal-fired SC PCC technology since the late 1970s when this technology fell out of favour in the USA. SC PCC units are now in operation in Denmark, Germany, Greece, Italy, the Netherlands, Poland and Spain (the Lada Unit 4). In Germany, Greece and Poland, where lignite represents either an important or the only indigenous energy, the SC PCC technology has been applied to lignite-based power generation (*see* Table 3, page 20). As the biggest lignite producer and consumer in Europe, Germany leads the way in the development of advanced SC PCC lignite-fired units. These developments are mainly the result of government policy initiatives rather than market drivers. Lignite is an important domestic energy source and helps provide security of energy supply. Lignite mining and utilisation also provide employment in areas where there is no other industry. For example, the former East German mining areas of Lusatia and Leipzig have been dependent on lignite mining and power generation since the 1950s. Germany has accumulated considerable experience through long-term lignite production and utilisation for power generation. The state-of-the-art technology, termed BoA (the lignite-fired power stations with optimised plant engineering), has been developed by RWE. The first BoA unit, the Niederaussem Unit K, went on stream in 2003, and another two BoA units with modern designs based on experience gained from the first unit are now under construction at the existing Neurath site in Grevenbroich, Germany. The three units will be discussed below in some detail.

In addition to the operational SC units in Germany, Greece and Poland, there are a number of lignite-fired SC units currently under construction in the Czech Republic, Germany and Poland. These units are summarised in Table 3. It is noted that all the operational units have modest SC steam conditions with main steam pressures lower than 28 MPa, temperatures of 545–554ºC, and reheat temperatures around 580ºC. Moreover, the individual unit capacity has been increasing steadily over time. The Niederaussem Unit K currently represents both the most advanced steam conditions and the largest single unit in terms of output capacity. The vast majority of the units under construction adopt USC steam conditions with main steam temperatures around 600ºC and pressures varying in the range of 27–31 MPa. This reflects the efforts by the technology developers in Europe to gradually push up the steam conditions for lignite-fired PCC units. RWE continues developing its BoA concept with very large single unit capacity, while Vattenfall appears to pursue high steam conditions with relatively smaller single unit capacity. The net cycle efficiency of operational SC units are around 43% (LHV); the USC units that are due to come online very soon are expected to have even higher efficiency. Another important feature of these SC/USC units is that they are designed to deliver good environmental performance. Old SC units are all equipped with FGD for SO_2 control and ESP for removal of particulates. Newer SC/USC units also incorporate NOx control measures such as low NOx burners, OFA, or SCR. These systems ensure that the plants will comply with the stringent EU emissions standards. Given the perceived high efficiency and good environmental performance, lignite-fired SC units have also been proposed in Poland, Greece, Czech Republic, Kosovo, Serbia and Montenegro, and Slovenia.

Niederaussem Unit K

RWE's Niederaussen Unit K, commissioned in 2003, is by far the largest lignite-fired unit in the world with a net output 965 MWe (or 1000 MWe gross). This is the first lignite-fuelled generation unit built based on RWE's BoA technology. Figure 4 shows a schematic diagram of the unit. It has a SC tangential wall-fired sliding pressure tower boiler using main steam conditions of 27.5 MPa and 580ºC with reheat to 600ºC. To withstand higher steam conditions, advanced alloy materials, such as P91, alloy steel with 9–12% CrMoV and E911 (X11CrMoWVNb9-1-1), are used for the boiler. In addition, a number of innovative designs have been incorporated in order to improve the overall unit efficiency. These include:

- advanced steam turbine with improved turbine efficiency (increase in efficiency of 1.7%);
- an elaborate feedwater heating circuit that captures heat from the bypass economiser, resulting in a final feedwater temperature of 295ºC (increase in efficiency of 1.1%);
- effective heat recovery from low temperature flue gas through the flue gas cooler (increase in efficiency of by 0.9%);
- low turbine exhaust pressure through the use of a high cooling tower (200 m) for a cooling water temperature less than 15ºC (increase in efficiency of by 1.4%);
- reduced auxiliary power consumption by using high efficiency electrical drives and minimising fan power demand due to reduced combustion air requirement (increase in efficiency of by 1.3%).

As a result, the Niederaussen Unit K achieves a net efficiency of 43.2%, despite firing lignite of over 50% moisture content, compared to typical efficiencies of existing lignite-fired plants of 31–35% (LHV). This is the highest net efficiency currently achievable by a lignite-fired PCC unit.

A further important feature of the unit is the large-scale demonstration facility for the open-cycle

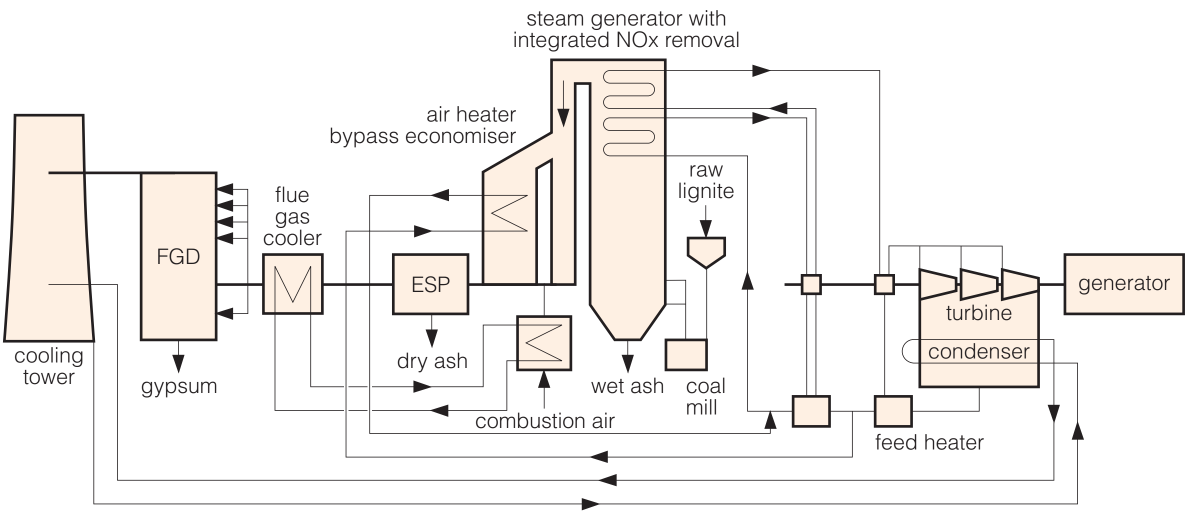

Figure 4 The schematic diagram of the Niederaussen Unit K, courtesy of (RWE, 2008)

Table 3 Current and future lignite-fired SC PCC plants in Europe

Plant	Location/owners	Gross output, MWe	Coal properties
Schkopau	Korbetha, Germany, E.ON Energie	2 x 450	Lignite, moisture 50%, LHV 11–12 MJ/kg
Schwarze Pumpe	Dresden, Germany Vattenfall Europe Energiewerke Schwarze Pumpe AG	2 x 800	Cottbus lignite, ash 3–12%, moisture 55–60%, LHV 7.1–9.6 MJ/kg
Boxberg	Weisswasser, Sachsen, Germany Vattenfall Europe	1 x 900	Lignite, S 0.4–1.4%, ash 3–10%, moisture 54–58 %, LHV 7.6–8.95 MJ/kg
Lippendorf	Leipzig, Germany Vattenfall Europe and others	2 x 930	Lignite (high slagging) Sulphur 1.7–2%, ash 8.8%, moisture 52%, LHV ~10.5 MJ/kg
Niederaussem Unit K	Niederaussem, Nordrhein-Westfalen, Germany RWE Energie	1 x 1000	Rhenish lignite, ash ~7%, moisture ~55%, LHV ~9.5 MJ/kg
Florina	Meliti-Achlada, Florina, Greece The Public Power Corporation (PPC)	1 x 330	Lignite, S 0.4–2.7%, ash 12.7–40%, moisture 30–44%, LHV 6.7–9.6 MJ/kg
Elektrownia Patnów II	Patnów, Poland ZE PAK SA	1 x 464	Lignite
Boxberg R	Weisswasser, Sachsen, Germany Vattenfall Europe	1 x 675	Lignite
Moorburg	Hamburg, Germany Vattenfall Europe and Hitachi Power Europe	2 x 820	Lignite
Neurath BoA 2&3	Grevenbroich, Germany RWE	2 x 1100	Lignite
Ledvice	Cezch Republic ČEZ	1 x 660	Brown coal
Belchatów II	Belchatów, Poland BOT Elektrownia Belchatów	1 x 858	Lignite, ash 5–11%, moisture 50–55% S ~0.6%

WTA process that uses a fluidised bed system to dry incoming lignite (*see* Chapter 5). The demonstration facility dries a quarter of the lignite fuel feed (a fuel flow equivalent to 250 MW) to reduce the coal moisture content from over 50% to 12%. This reduces the energy penalty of in-furnace drying so as to raise efficiency further. Only low grade heat (110–120ºC) in the form of low pressure steam is used to dry the lignite; much of the latent heat of evaporated moisture is recovered to preheat the feedwater. This demonstration WTA plant is estimated to further increase the unit efficiency by 1 percentage point and reduce the CO_2 emission by more than 250 kt/y (Henderson, 2008).

Table 3

Steam conditions	Status	Comments
26.5 MPa/545°C/ 560°C	Operational commissioned in 1995-96	CHP, wet limestone scrubber, ESP, thermal efficiency ~40% (LHV)
26 MPa/547°C /565°C	Operational commissioned in 1997-98	Wet limestone scrubber, ESP, part of a large complex with all subcritical decommissioned, net efficiency over 40% (LHV), heat/power cogeneration fuel efficiency 44%
26.8 MPa/545°C/ 560°C	Operational commissioned in 2000	Part of a 1900 MW power station, wet limestone scrubber, ESP, net efficiency 40–42% (LHV)
26.8 MPa/554°C/583°C	Operational commissioned in 2000	Wet limestone scrubber, ESP, built to replace four old subcritical units, also provides district heating, efficiency 40–45% (LHV)
27.5 MPa/580°C/ 600°C	Operational commissioned in 2002-03	Currently, the most efficient lignite-fired unit with a net efficiency reported at 43% (LHV), part of a big complex (2795 MWe of subcritical), wet limestone scrubber, ESP
24.2 MPa/543°C /542°C	Operational comissioned in 2003	Wet limestone scrubber, ESP, plant efficiency ~38% (LHV)
–	Operational commissioned in 2008	Replacing two old subcritical units, a turn-key project by Alstom, low NOx burners plus OFA for NOx control, wet lime FGD system, availability >90%, net efficiency 41% (LHV)
28.5 MPa/600°C/ 545°C/581°C	Under construction start-up 2011	Rafako (Poland) supplied boiler, expected efficiency >43% (LHV)
30.5 MPa/600°C/ 610°C	Under construction start-up 2010	Rafako contracted with Hitachi for supply of pressure parts
27.2 MPa/600°C/ 605°C	Under construction start-up 2010	Both units use boilers supplied by Hitachi, Alstom Brno is supplying pressure parts and steam turbine islands and carrying out overall plant engineering, lignite drying unit incorporated, FGD, total cost more than €2.2 billion, expected efficiency over 43%
28 MPa/600°C/ 610°C	Under construction start-up 2012	Alstom tower-type boiler, wet limestone scrubber with product mixed with fly ash to produce an additive granulate material for mine reclamation, NOx control
–	Under construction start-up 2010	Part of the Belchatów power complex (858 MW + 4440 MW), Rafako supplies the boiler, Alstom supplies the steam turbine, generator, cooling system and control system, ESP, FGD and NOx control, expected net efficiency 41.56% (LHV), estimated cost €900 million

Neurath BoA 2&3

Neurath BoA 2&3 represent the latest development of RWE's BoA concept. They are being constructed to replace the existing old units at the Neurath site in Grevenbroich, Germany. The two new units will each have a gross capacity of 1100 MW and, like all other large lignite-fired power plants, will be operated in base load. Although their basic design is similar to that of existing old units at the site, there are significant improvements to the various plant components and process steps. This results in better use of the fuel with the unit efficiency above 43%, some 31% higher than old units at the site, and a CO_2 reduction up to 6 Mt/y. Specially designed lignite burners and optimally matched injection of coal and combustion air will combine to limit the formation of NOx. A wet limestone scrubber process will be installed to remove more than 90% of the SO_2 from the flue gas and produce gypsum. Modern ESPs will be used to remove more than 99.8% of the particulate matter from the flue gas. Compared to old units, the specific SO_2, NOx and dust emissions will be reduced by about 31%. The construction work will take about four years and the start of commercial operations can be expected in 2011. As required by provisions in the construction approval notification of the Düsseldorf regional government, six 150 MW units at the Frimmersdorf power stati

on will be shut down before commissioning the first new BoA unit. In a period of some two years after the start of commercial operations of the new power plant units, four more 150 MW units at Frimmersdorf or Niederaussem are to be finally decommissioned. Two further 150 MW units are to follow in the same period if the supply situation in RWE's grid permits this.

2.3 Future development

Future development of lignite-fired PCC units is concentrated on three major areas: larger units, more advanced steam conditions, and carbon capture and storage (CCS). SC and USC power plants are today chosen routinely in many countries with unit sizes up to 1000 MWe and steam conditions typically of 24–30 MPa/543–600ºC/543–610ºC. The SC/USC PCC technology under these conditions is mature, so future development will consist of refinements rather than major breakthroughs. Emphasis is now mainly on improving the efficiencies of such facilities. For example, the BoA technology is built on existing PCC technology with improved process designs to achieve overall cycle efficiency in excess of 43%. In order to raise thermal efficiency further ⩾50%), the steam conditions need to be further developed beyond the current state-of-the-art SC/USC conditions. Increased efficiencies will result in improved operational economics as well as a reduction in CO_2 emissions.

The material issue is considered as the major barrier to adoption of even higher steam conditions (main steam temperature at 700ºC or above) for PCC units. The materials required to construct USC plants with steam temperatures up to 625ºC and pressures up to 34 MPa is largely available today in the form of commercial steels. Although iron-based alloys could be further developed to withstand even higher conditions, it was recognised during the early 1990s that there would be greater scope for advancement by exploiting nickel-based alloys. The increased steam conditions affect primarily the waterwalls, final superheater and reheater tubing and the thick-walled components (mainly the high pressure outlet headers and the piping to the turbine). High temperature materials development is a long-term process; it may take about 12 years to achieve a completely reliable mature material (Nalbandian, 2008). There have been a number of concerted R&D programmes dedicated to development of advanced high-temperature materials. 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. E.ON had a plan to build the first CO_2 capture ready 50plus unit; however this plan has now been delayed indefinitely. 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 1300ºF (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 are at an advanced stage of development and are expected to be available to support construction of an UltraGen II demonstration plant within a few years.

Reductions in CO_2 emissions from efficiency advances by installation of SC technology instead of subcritical systems are limited to around 30% (Nalbandian, 2008). Subcritical, supercritical and ultra-supercritical technologies have emission intensities of approximately 0.850–0.970 t/MWh, 0.760 t/MWh and 0.720 t/MWh respectively (Nalbandian, 2008). To further reduce CO_2 emissions from PCC power plants beyond these limits, carbon capture and storage is required. CCS is yet to be technologically proven, requiring full-scale demonstration of the integrated process. Installing CCS on a PCC power plant would increase costs by 50%–80%, which is a significant barrier to CCS deployment (Wamsted, 2006). Research and development continues throughout the world to address both technological and cost issues of CCS installation on PCC power plants. The major CCS projects and proposals using lignite or subbituminous coals have been summarised in a sister report by Mills (2010). There are primarily two different approaches: oxyfuel combustion technology and post-combustion capture. Oxyfuel projects involving lignite include the Schwarze Pumpe 30 MWth pilot plant in Germany and the FutureGen II (200 MW) and Barberton pilot plant (30 MWth) in the USA. The majority of the CCS research activities for lignite are based on post-combustion capture and are located in the USA, Canada, Czech Republic, Germany, Poland and Australia. Most of those projects are based on amine scrubbing and the CO_2 captured is use for EOR. Use of ammonia as sorbent and CO_2 in geological aquifers are also being tested.

3 Circulating fluidised bed combustion power plant

Fluidised bed combustion (FBC) is a well established method of burning solid fuels. It uses a continuous stream of air to create turbulence in a bed of mixed fuel, inert material and coarse fuel ash particles. At an appropriate gas velocity, the particles remain suspended and move about freely or become entrained in the gas stream. In contrast to PCC, relatively coarser particles of <3–6 mm are used in FBC. When fresh fuel is charged into the hot fluidised bed, the constant mixing of particles encourages rapid heat transfer and good combustion. It also allows a uniform temperature to be maintained within the combustion zone. Heat generated is recovered by in-bed tubes (with a bubbling FBC boiler), waterwalls, superheater/reheater sections, economiser and others. Flue gases leaving the boiler furnace are cleaned as in a PCC plant.

There are two basic formats used in FBC, depending on the gas velocity. In a bubbling FBC (BFBC), the gas velocity is around 1–3 m/s, whereas the velocity is higher (at 4–6 m/s) in a circulating FBC (CFBC). BFBC is commonly used in industrial applications to small boilers up to 20–25 MWe , while the majority CFBC boilers are used for power generation. There are only a few exceptions where larger capacity BFBC units are being operated, and these are all repowering projects where there were strict engineering limits on possible technological choices within the available space (Rousaki and Couch, 2000). Since pressurised FBC is actually a 'dead' technology, this chapter will focus on atmospheric CFBC.

CFBC has a number of advantages. It is able to utilise high ash material such as coal mining/washery wastes, which if used in a PCC boiler would lead to high maintenance costs and potentially unstable combustion. Waste recovery applications favour the use of relatively small units constructed in close proximity to the waste source. CFBC boilers are able to burn a wide range of low-grade or low rank coals, and to cofire biomass and municipal wastes at fairly high percentages with coal as an option for reducing CO_2 emissions. Combustion in FBC takes place at typically 800–900°C, much lower than the 1300–1700°C used in PCC, which is below the temperature at which the ash becomes sticky. The lower combustion temperature results in the formation of considerably less NOx compared to PCC. Limestone or dolomite can be added into the bed to facilitate in-furnace desulphurisation; about 90–95% SO_2 reduction has been achieved. No additional SO_2 control measures are needed, but the disposal of solid residue warrants careful consideration.

FBC boilers are usually less efficient than PCC boilers because the greater fan power needs outweigh the savings in coal pulveriser power consumption. FBC power generation units are also limited in output capacity to generally 200–300 MWe; the present-day largest CFBC unit in operation, the Lagisza unit in Poland, has an output capacity of 460 MWe. FBC also lags behind PCC in terms of utilisation of SC/USC steam conditions. While there is a large number of USC PCC units currently in operation in many parts of the world, the Lagisza unit is the world's first supercritical CFBC unit. However, CFBC has advantages over PCC in its capacity to burn a wide range of fuels and because it's cost effective. CFBC has been chosen in many situations among different technologies for burning low quality solid fuels. However, electricity generation using CFBC accounts for a small fraction of total coal-fired generation capacity.

3.1 The impact of coal characteristics

As already mentioned, CFBC is particularly suited to burning low quality coals that may be difficult to handle in a PCC unit. These include low rank coals containing soft fibrous material and high ash coals with hard abrasive mineral matter; either can increase pulverising costs significantly if used in a PCC unit. Another type of fuel is anthracitic coals with low volatile content which may not burn out completely in a PCC boiler due to the short residence time of coal particles. In CFBC, these coals are recycled many times through the combustion chamber so that more complete burnout results. Coals with highly slagging and/or fouling ash may also not be suitable for use in PCC units. These coals can be burnt effectively in CFBC because the relatively low combustion temperature means that the mineral matter stays in its original state with no softening or decomposition.

3.1.1 Moisture

Coal moisture content has important effects on both the design and operation of CFBC boilers. Since moisture is evaporated and then present in the flue gas, a coal with a high moisture content will significantly increase the flue gas volume and as a result the gas velocity. Such changes need to be taken into account in the boiler design; generally, a larger boiler is required to cope with the flows while keeping gas velocities within an acceptable range. If the moisture content of a coal varies considerably, then boiler control is more difficult because velocities in the furnace and through the cyclone can be subject to rapid change.

3.1.2 Ash

The ash-induced problems in CFBC plants comprise mainly erosion/corrosion and deposition/agglomeration. Hard and abrasive ash can cause erosion at various places in the plant. This is due to the constant impact on surfaces by particles continuously circulated around the system. The erosion can be enhanced by the limestone added to remove sulphur. Various measures can be taken to minimise the erosion effects, and using lower gas velocities is sometimes necessary. Corrosion generally occurs on heat transfer surfaces or weld junctions that are covered by deposited ash. Corrosion is closely linked to the alkalis and chloride present in the coal. A significant level of erosion/corrosion leads to increased maintenance costs and reduced boiler availability.

Although CFBC boilers typically operate at relatively low temperatures, certain ash components, such as sodium, calcium and organically bound sulphur, have the potential to cause ash-related problems including bed material agglomeration, defluidisation and deposition on heat exchanger tube surfaces. These components can form low melting eutectics at typical FBC temperatures (Vuthaluru and Zhang, 2001). These eutectics are transferred to the surface of inert bed particles during collision of the burning char particles with bed material in the combustion zone, leading to agglomeration and subsequently defluidisation of the bed. Deposition mechanisms for particles onto heat transfer surfaces are much the same as those in PCC boilers, except that the temperatures involved in CFBC are lower. These ash-related problems may lead to loss of steam temperature, operating difficulties, unplanned and unnecessary shut-downs. For example, heavy agglomerated particles may drop to the boiler bottom and settle on the fluidising grid. Under certain conditions, these particles may then catch fire and the ash may melt to form a clinker-clogging the grid and interfering with the air distribution. Sodium, calcium and organically-bound sulphur are commonly found in low rank coals. Therefore, these ash-related problems need to be taken into account when firing low rank coals in CFBC plants.

Measures have been developed to remedy the ash-related problems in lignite-fired CFBC boilers. These include the use of alternative bed materials, mineral additives, pre-treatment of coal and coal blending. In a study involving fluidised bed combustion of South Australian lignite, sillimanite, bauxite, calcite and magnesite were used as alternative bed materials. It was found that their use was effective in reducing ash agglomeration and resulted in extended combustion operation. Increased levels of Al, Ca, and Mg in bed material appear to have diluted the cementing material in the ash, resulting in a less sticky ash coating. The use of mineral additives, clay and kaosil and bauxite, was also found effective in mitigating the ash-related problem by enriching ash deposit on bed materials with high-melting alumina and silica. Water washing and aluminium/calcium pre-treatment of coal were shown to reduce agglomeration and defluidisation propensities, mainly due to Al/Ca enrichment and removal of Na, which altered ash characteristics. Blending high Na/S lignite with subbituminous coal that has low Na/S content or high melting point was shown to increase the high-melting phases in the ash coating on bed material, thus retarding ash agglomeration and bed defluidisation. Although the above measures are all technically suitable to mitigate ash-related problems, their applicability depends on the economic considerations. Generally, the control methods involving alternative bed materials and mineral additives are less expensive than wet pre-treatment and blending methods, which involve high coal preparation and transportation costs.

3.1.3 Sulphur content

The sulphur content of a coal affects the amount of sorbent needed to ensure SO_2 emissions are below the permitted level. Commonly a Ca:S ratio of about 2 is needed, but the ratio is increased with high S coals. An increased use of calcium necessitate a larger solid residue handling system, which needs to be taken into account in plant design.

3.1.4 Feed variability

Feed variability is a difficult issue to deal with when low quality coal is used. The variations in coal quality and calorific value exist not only in coals from different seams but also in outputs from the same coal seam. This issue becomes more severe when using dumped mining/washery coal wastes. Feed variation can affect the power plant output and result in unstable operation. CFBC systems are more tolerant of feed variation with their longer residence time for coal particles and the heat sink provided by the refractory. Nevertheless, it remains important to take appropriate measures to minimise feed variability when burning low quality coals in CFBC plants.

3.2 Design consideration and development

CFBC in the 30–250 MWe size range is a widely used and well established technology. CFBC systems in this size range all use subcritical steam cycles. Design consideration mainly comprise sizing the boiler according to coal characteristics, cyclone development, and scale-up.

3.2.1 Boiler sizing

Boiler size is dependent on coal characteristics. The key design factors relating to the use of low quality coals include:
- combustion characteristics, depending largely on the coal rank;
- the ash content and the sulphur content, which affects the solids loading in the boiler and cyclones and can affect erosion;
- the ash composition, which affects corrosion, fouling, ash agglomeration and bed defluidisation;
- moisture content, which affects the flue gas volume;
- the provision of coal feed and ash handling systems;
- the load following capability down to typically 40% of a unit's maximum continuous rating,

Similarly to PCC systems, the size of CFBC systems generally increases with the moisture and alkali contents of the coal. Take wall-fired CFBC for example the boiler width and height would increase by 20% and 8% respectively, when the fuel is changed from a medium volatile bituminous coal (moisture 5%, ash 10%) to a high sodium lignite (moisture 40%, ash 6%) (Rousaki and Couch, 2000). The furnace depth (the distance from the front wall to the back wall) normally remains unchanged in order to maintain even distribution of both air and fuel across the furnace, which is important for both stable bed fluidisation and temperature control. The maximum practical height for a CFBC furnace appears to be about 50 m. The limitation is a decrease in bed density with height; a lower bed density results in less efficient heat transfer. It is also noted that the necessary change in CFBC boiler size is less than that for an equivalent PCC boiler (Rousaki and Couch, 2000).

3.2.2 Cyclone development

Conventional designs of CFBC use an exterior cyclone for recirculating the bed materials and unburnt chars. Water- or steam-cooled cyclones are mostly used although some old small CFBC boilers still use thick multi-layer refractory non-cooled cyclones. With the cooled construction, the cyclone interior walls are lined with a thin layer of refractory held in place by a dense pattern of metal studs, while the exterior walls are covered with insulation and lagging to prevent heat losses. This improved cooling design minimises refractory maintenance. To improve the cyclone separation efficiency and reduce its physical size (hence the entire system becomes more compact), a number of novel designs have been developed. These include Foster Wheeler's Compact Separator, Babcock & Wilcox's U-beams impact separator, Tsinghua University's water-cooled square cyclone, IET's louvre-type separators, and Π-shaped down-exhaust cyclone (Wu, 2006). All of these novel cyclones have been applied to commercial CFBC installations.

3.2.3 Scaling-up

Scaling-up CFBC boilers has been an important consideration since development started in the 1970s. Technically, this involves several aspects, including furnace height, furnace width, cyclone diameter and the number of fuel feed points together with the number of return points for recirculated solids. The major challenge is to maintain stable fluidisation throughout the large cross-sectional area of the CFBC boiler furnace, together with an even distribution of both air and fuel in the lower part of the boiler furnace. Both the burner arrangement and the secondary air induction need to be considered to avoid local high fuel concentrations and hot spots. The placement of the heat exchange surfaces at appropriate locations in the boiler is also important. The design objective is to provide operating flexibility, low capital and maintenance costs and the ability to cope with fuel variability. As boiler size increases, the furnace to volume ratio decreases and it may not be possible to perform all the required heat duty in the furnace and back pass. Hence, an external heat exchanger may be used to provide additional heat duty. Examples of such additional external heat transfer devices include Foster Wheeler's INTREX™ (Integrated Recycle Heat Exchanger) system and Lurgi's external fluid bed heat exchanger (Rousaki and Couch, 2000; Wu, 2005). In these devices, the immersed tube bundles can provide heat to either superheat or reheat steams.

Different approaches are made to the design details by CFBC suppliers. For example, in scaling-up from 100 MWe to 300 MWe size, Foster Wheeler increased the furnace width, while keeping the furnace depth constant. Alstom's approach was to keep the furnace width essentially constant, but to adopt the pant-leg design, which involves using two separate fluidising grids in separate (short) legs and feeding into one furnace area. A further scale-up design by Foster Wheeler up to 600 MWe incorporates new firing arrangements, such as tangential, four-wall or opposed firing, in order to increase the furnace depth. Alstom intends to widen their existing 250 MWe pant-leg design for larger units.

3.3 Current experience

The major markets for CFBC technology are Asia, North America and Europe. There are currently over 1200 CFBC plants worldwide with a total installed capacity of some 65 GWth, of which about 52% are in Asia, 26% in North America and 22% in Europe (Wu, 2006). Almost all of the Asian CFBC capacity is located in China; similarly, the USA accounts for nearly all installations in North America. The majority of European CFBC capacity is located in eastern Europe and the Scandinavian

Table 4 The operating large CFBC units burning low quality coals (Rousaki and Couch, 2000; Wu, 2005; Ostrowski and Góral, 2010)

Plant	Location	Plant size, MW	Steam conditions	Coal type
Zhungeer Dafanpu	Inner Mongolia, China	2 x 300	Similar to that used in Baima power station	Lignite
Pingshuo II	Shanxi, China	2 x 300	Similar to that used in Baima power station	Coal mine/washery wastes
Xilinggele	Inner Mongolia, China	2 x 300	Similar to that used in Baima power station	Lignite
Jixi B	Heilongjiang, China	2 x 300	Similar to that used in Baima power station	Lignite/coal mine wastes
Linhuan	Huaibei, Anhui, China	2 x 300	Similar to that used in Baima power station	Coal mine/washery wastes
Sandow 5	Texas, USA	2 x 315	16.5 MPa/538°C	Lignite
Guodian Kaiyuan	Yunnan, China	2 x 300	Similar to that used in Baima power station	Lignite
Xunjiansi	Yunnan, China	2 x 300	Similar to that used in Baima power station	Lignite
Honghe	Yunnan, China	2 x 300	Similar to that used in Baima power station	Lignite
Baima	Sichuan, China	1 x 300	17.4 MPa/540°C/540°C	low-volatile (8%) high ash (35%) anthracite
Seward	Pennsylvania,USA	2 x 292	17.4 MPa/541°C/541°C	Coal mining waste
Turów Units 4-6	Poland	3 x 265	16.7 MPa/565°C/585°C	Brown coal (40–48% moisture, 6.5–31.5% ash, 0.4–0.8% S)
Red Hills	Mississippi, USA	2 x 250	18.1 MPa/568°C/540°C	Lignite with high Ca content
PKE Lagisza*	Katowice, Poland	1 x 460	27.5 MPa/557°C/578°C (feedwater temperature 278.8°C)	Hard coals from 10 local mines (LHV 18–23 MJ/kg, moisture 6–23%, ash 10–25%, S 0.6–1.4%, chlorine <0.4%)

* given for comparison with existing CFBC units burning low quality coals

Table 4
Comments
Commissioned in 2009, boilers supplied by Shanghai Boiler Co, minemouth power plant, air cooled, FGD, ESP
Commissioned in 2009, boilers supplied by Shanghai Boiler Co, air cooled, ESP
Commissioned in 2009, boilers supplied by Harbin Boiler Co
Commissioned in 2009, boilers supplied by Harbin Boiler Co
Commissioned in 2009, boilers supplied by Harbin Boiler Co
Commissioned in 2009; Owned by Luminant; boilers supplied by Foster Wheeler; SNCR for NOx control; a fluidised bed FGD scrubber system for additional SO_2 capture; bag house for particulates removal
Commissioned in 2007, boilers supplied by Shanghai Boiler Co under a co-production agreement with Alstom
Commissioned in 2007, boilers supplied by Harbin Boiler Co
Commissioned in 2006, boilers supplied by Harbin Boiler Co
Commissioned in 2006, the boiler designed by Alstom, co-manufactured by Alstom and Dongfang Boiler Co, pant-leg with external heat exchanger, air staging NOx control, boiler thermal efficiency >91%, SO_2 ≤550 mg/m^3, NOx ≤90 mg/m^3
Commissioned in 2004; owned by Reliant Energy; boilers supplied by Alstom; aqueous ammonia-based SNCR for NOx control; NOx ≤0.155 g/kWh; four FDA reactors (a type of dry FGD system) per boiler for additional SO_2 removal, S removal efficiency >95%, SO_2 ≤0.929 g/kWh bag filter, dust ≤0.015 g/kWh; CO ≤0.232 g/kWh; VOC <0.008 g/kWh
Commissioned during 2004-06; 2 hot cyclone units plus one Foster Wheeler's Compact unit; the INTREX™ heat exchanger; NOx ≤371 mg/m^3; SOx ≤347 mg/m^3; CO ≤150 mg/m^3; dust ≤50 mg/m^3
Commissioned in 2002, owned by Choctaw Generation LLP; boiler supplied by Alstom; pant-leg design with external FBHEs, no additional back-end NOx or SO_2 control; >95% S capture efficiency (0.020–0.155 lg/kWh), NOx emissions ≤0.310 g/kWh
Commissioned in 2009; owned by PKE; supercritical once-through Benson vertical boiler supplied by Foster Wheeler; net plant efficiency 43.3% and net power output 439 MWe; NOx ≤167–190 mg/m^3; SO_2 ≤134–148 mg/m^3; CO ≤33–-86 mg/m^3; dust ≤1.85–-3.14 mg/m^3

region. Major suppliers of CFBC boilers are Foster Wheeler, Lurgi, Alstom and Babcock & Wilcox. Foster Wheeler accounts for nearly half of the world's market.

To date, CFBC boilers in operation range in size from a few MW to 460 MW, while the 200–300 MW class is most common for power generation. The only 460 MWe unit is the supercritical Lagisza unit commissioned in June 2009. It adopts steam conditions of 27.5 MPa/557°C/578°C and has a net plant efficiency of 43.3% (LHV). However, currently large CFBC boilers firing low quality coals have maximum output capacities up to 300 MW, of which the latest units are summarised in Table 4. These latest large CFBC boilers use or are based on (in the case of China) either Foster Wheeler or Alstom designs. The steam conditions adopted by these large low quality coal fired CFBC units are in the range of 16.5–17.4 MPa/540–568°C/540–585°C, comparable to those firing hard coals. With a subcritical cycle, the CFBC plant efficiency is of the same order as that of a PCC plant, normally between 38% and 40% on a LHV basis (Wu, 2005).

As a result of technology advances and extensive operational experience accumulated worldwide, CFBC plants now commonly achieve an availability of >90% (Wu, 2005). For example, the Foster Wheeler-designed units have over 98% annual availabilities, while some Lurgi-designed plants in the USA have achieved <95% availabilities (Wu, 2005). However, the lack of tuning and operational optimisation may result in lower availability in the early years of operation. This is particularly true in the case where the fuel variability is large. Modifications to the boilers as well as fuel handling/feeding systems may be required. The use of external fluidised bed heat exchangers (FBHE) can help mitigate the availability problem due to high fuel variability. This is because the FBHE can accommodate the differences in flue gas rates and heat rates as a consequence of changes in fuel feedstock.

CFBC has relatively low NOx emissions by nature of the low combustion temperature and air staging, typically around one fifth of those produced by uncontrolled PC combustion. The actually level depends on the fuel characteristics, bed temperature and other factors. The uncontrolled NOx emissions are less than 400 mg/m^3 for most CFBC plants. As can be seen from Table 4, modern low quality coal fired CFBC plants tend to have NOx emissions of less than 200 mg/m^3. Additional NOx control such as SNCR or SCR may be needed for units that burn coal mining or washery wastes. For instance, the Seward power plant is equipped with aqueous ammonia-based SNCR, resulting in emissions of less than 0.155 /kWh.

Typically, CFBC can achieve sulphur retention efficiencies of 90% at a Ca/S molar ratio of around 2. Efficiencies of more than 95% have been achieved with either a higher Ca/S ratio (Red Hills) or the use of additional dry scrubber (for instance, Seward). Thus the desulphurisation efficiency is comparable to that obtainable in a PCC power plant fitted with a wet scrubber, whilst CFBC plants use significantly less sorbent. Additional SO_2 removal may be required for plants burning coal mining/washery wastes that may contain a much higher concentration of sulphur. The actual level of SO_2 emissions depends on the fuel used and sulphur retention efficiency, with lower than 400 mg/m^3 generally expected with no additional desulphurisation. The Lagisza plant has SO_2 emissions of less than 200 mg/m^3, which may indicate the lowest level of SO_2 emissions for current advanced CFBC plants.

Particulates and CO emissions from low quality coal fired CFBC plants are also satisfactory. At most plants, dust emissions of 20–50 mg/m^3 have been easily achieved, while the reported CO emissions fall in a wide range between 20 mg/m^3 and 250 mg/m^3, depending on the fuel burnt (Wu, 2005). Lignite-fired CFBC plants are found to emit less CO than hard coal plants (Scott, 2001).

A number of case studies are given below, covering different fuels and geographical locations. The Lagisza supercritical power plant burning bituminous coals is included for comparison purpose.

3.3.1 PKE Lagisza

The Lagisza CFBC unit in Poland is the world's first supercritical CFBC facility and has the world's largest CFBC boiler rated at 460 MWe. The unit is owned by Poland's largest utility, Poludniowy Koncern Energetyczny (PKE) and burns bituminous coals (LHV 18–23 MJ/kg) from ten local mines. The new 460 MWe unit was built to replace old PCC units constructed during the 1960s; two of the seven old units have been shut down after the new unit was commissioned in June 2009. The Benson once-through boiler design for Lagisza is based on Foster Wheeler's second generation Compact CFB technology that avoids heavy multi-layer refractory linings by integrating the solids separator with the combustion chamber. In contrast to conventional hot cyclones, the solid separators are designed with steam-cooled panel wall sections (forming the third superheater stage) and have a thin refractory lining anchored with dense studding. This Compact design thus reduces the amount of refractory required and minimises the number and size of expansion joints. The separator inlet design provides a uniform flow of flue gas and solids avoiding high local velocities, and therefore provides a separation efficiency equal to the best conventional cyclones with considerably lower pressure loss. Another important design feature is the INTREX™ superheater, which is a fluidised bed heat exchanger integrated into the lower part of the furnace (*see* Figure 5). It is the last superheater to control the main steam conditions before feeding the steam to the steam turbine. The main steam temperature is controlled with a two-stage feedwater spray as well as by adjusting fuel feeding. A flue gas heat recovery system (HRS) is employed to improve the boiler and power plant efficiency by decreasing the flue gas temperature to 85°C. The system operates in the clean gas after the ESP and ID fans. With steam conditions of 27.5 MPa/557°C/578°C, the calculated net plant efficiency for Lagisza is 43.3% and net power output is 439 MWe. The unit meets all design requirements for emissions with no additional emissions control, as shown in Table 4. Following the success at Lagisza, Foster Wheeler has concluded that CFB technology is today commercially proven to boiler sizes of 500 MWe. The next supercritical once-through CFB boiler was sold by Foster Wheeler in January 2008 in Russia (Novocherkavskaya Power Plant) with a capacity of 330 MWe.

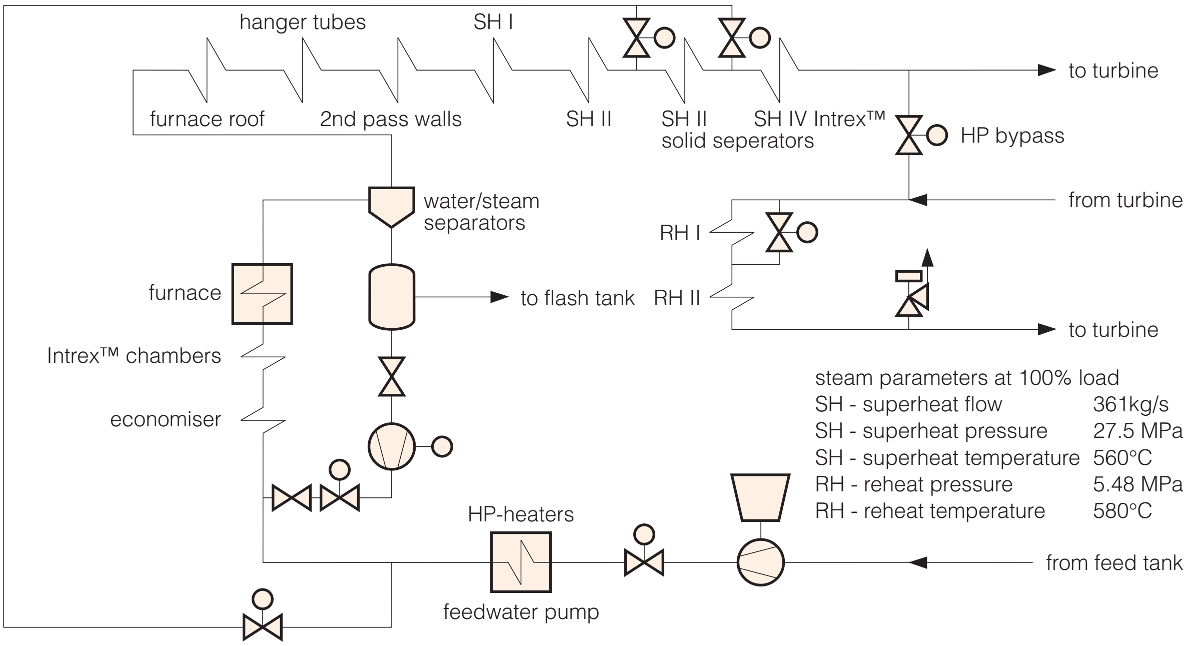

Figure 5 The steam circuitry of the PKE Lagisza power plant (Ostrowski and Góral, 2010)

3.3.2 Seward

The Seward power plant is located in Pennsylvania, USA and owned by Texas-based Reliant Energy Inc. When the plant began commercial operation in 2004, it replaced an existing old 200 MW power facility shut down in late 2003. It supplies power to PJM Interconnect in the mid-Atlantic region. The Seward power plant is powered by two Alstom 292 MW (gross) CFB boilers that burn local coal mining wastes. There is a vast amount of waste coal accumulated from local bituminous coal production over the past 100 years. Water running off the waste piles fouls streams and contaminates water supplies. The Seward plant is expected to remove and consume up to 100 Mt of waste coal over its entire life, thus eliminate a significant source of acid discharge. In addition, the alkaline ash produced at the plant is returned to many of the waste coal sites to neutralise any acids remaining in the soil. CFBC technology was chosen due to its fuel flexibility and low-cost efficient in-furnace desulphurisation and low NOx formation. To meet Pennsylvania's air emissions standards, the plant uses an aqueous ammonia-based SNCR for additional NOx control and Alstom's patented flash dryer absorber (FDA) FGD system for further SO_2 removal. The resulting NOx emissions are less than 0.1 lb per million Btu with ammonia slip not to exceed 10 ppm, while the SO_2 retention efficiency is over 95% and the emission level is limited to 0.929 g/kWh, irrespective of the sulphur content in the fuel. About 70% of the SO_2 formed during combustion is captured internally by the calcium oxide generated from the calcination of the limestone in the CFB furnace. Total CO emissions are limited to 0.235 g/kWh 70–100% load, and 0.310 g/kWh at 40–70% load. Volatile organic compound (VOC) emissions in the flue gas are limited to 0.008 g/kWh without supplemental or post-combustion VOC reduction equipment. A baghouse with the FDA controls particulate emissions to less than 0.015 g/kWh (Rod and Proffit, 2002). CFBC, together with additional emissions control technologies, thus allows the Seward plant to turn polluting wastes into electricity, while complying with stringent air emission standards in Pennsylvania.

3.3.3 Turów

The Turów power plant in Poland is currently the world's largest lignite-fuelled power generation facility using CFBC technology. It consists of six CFBC units with a total installed output capacity of 1500 MW. These units have been built in three phases to replace ten old polluting PCC units at the site

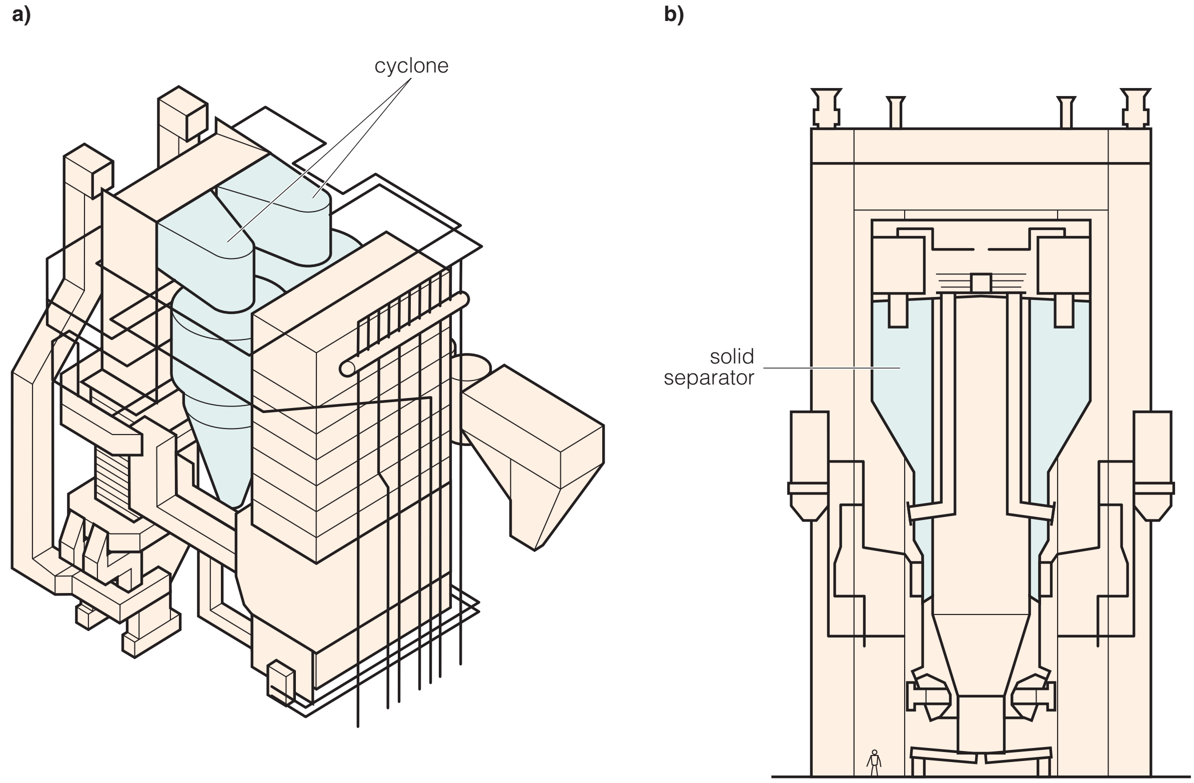

Figure 6 (a) The schematic view of the Turów Phase I & II boiler; (b) the schematic view of the Phase III boiler (Psik and others, 2005)

as the core of the Turów Rehabilitation Project. The first phase was the retrofit of Units 1 and 2 that were commissioned in 1998; the second-phase Unit 3 was commissioned during April 2000; in the third phase Unit 4–6 were brought online in March 2003, February 2004 and December 2004 respectively. Units 1–3 (235 MW each) represent conventional CFBC technology, that is the separators are round hot cyclones with heavy multi-layers refractory lining (*see* Figure 6a). These units use steam conditions of 18.5 MPa/540°C/540°C. In order to minimise the maintenance needs and simplify the overall design, Foster Wheeler developed the Compact design for the third-phase Units 4–6, where the traditional cyclones have been replaced with cooled rectangular solid separators adjacent to the boiler furnace (*see* Figure 6b). The Compact design at Turów incorporates experiences gained with the first three units into Foster Wheeler's existing Compact design for smaller FBC boilers. With the Compact design, it has been possible to increase the output of Units 4–6 to 261.6 MWe, compared to 235 MWe for the first three units, while utilising the same footprint available from old PCC boilers. The INTREX™ heat exchanger and rotary air preheaters also contribute to the increased unit output capacity. Units 4–6 use higher steam conditions of 16.7 MPa/565°C/585°C. The fuel is local lignite from opencast mines located no more than 10 km from the power plant; fuel is transported to the fuel yard via belt conveyors. The new plant has an average net efficiency of 39% compared to the 32% of the original PCC plant, resulting in a CO_2 reduction per MWe of almost 20%. The boiler efficiency of Units 1–3 is 91.2% on average, while that of Units 4–5 reaches around 93%. The new CFBC units emit about 87 t/y less SO_2 (93% reduction/MWe), 5.22 t/y less NOx (50% reduction/MWe), and 36.5 t/y less dust (94% reduction/MWe) compared to old PCC units (Psik and others, 2005).

3.3.4 Baima

The Baima power plant, located in Sichuan Province, was China's first 300 MW class large CFBC plant. Its main shareholders are State Power Grid and Sichuan Bashu Electric Power Development. It was built as a demonstration plant with the specific purpose of proving Alstom's CFBC technology could be successfully applied in China. Alstom, in co-operation with Dongfang Boiler Co, supplied the CFB boiler; the design and engineering was done in France, while the manufacturing was shared between Alstom and Dongfang facilities. The Baima plant is designed to fire a high S (3.54–4.3%) Chinese anthracite, which has a relatively low volatile matter content (8.5% as received) and a high ash content (35% as received). Its calorific value is around 18.5 MJ/kg. The boiler has the same design as those at Provence (1 x 250 MW) and Red Hills (2 x 250 MW) which had been operating successfully for several years at that time. Key features include pant-leg furnace, four high efficiency cyclones and four external exchangers (two for bed temperature control and two for reheat system temperature control). The boiler adopted steam conditions of 17.4 MPa/540°C/540°C and achieves a boiler efficiency higher than 91% (LHV). The flue gas discharged meets the guaranteed emissions requirements (SO_2 ≤600 mg/m^3 and NOx ≤250 mg/m^3) without any additional post-combustion cleaning equipment for SO_2 and NOx.

The Baima CFBC power plant involved technology transfer from Alstom. Alstom's 300 MW class CFBC boiler technology has been transferred to the three largest Chinese boilermakers, Harbin Boiler Co, Shanghai Boiler Co and Dongfang Boiler Co, under licence agreements (Minchener, 2010). Each of the three boilermakers was required to execute a co-production project together with Alstom. These projects provided the opportunities for China's boiler makers to modify or further develop Alstom's design to better suit China's requirements. The imported technology based development has been complemented by domestic technology development between Chinese boilermakers and various university and research institutes. As a consequence, the 300 MW class CFBC technology is now being rapidly deployed in China. As of May 2009, there were 15 such units in operation with another sixty-four 300 MW CFBC units on order or under construction (Minchener, 2010). The NDRC has therefore made it clear that China will not import any more 300 MW class CFBC technology and further larger-scale development will be based on domestic R&D activities.

3.4 Future development

Development efforts are primarily concentrated on the scale-up of the technology, once-through supercritical designs, improved materials of construction, and CO_2 capture. With the successful operation of the Lagisza supercritical CFBC power plant, Foster Wheeler is confident to offer its 500 MWe CFBC technology commercially based on its Compact design. Alstom's scale-up strategy for the 600 MWe class is based on the pant-leg design. This has an arrangement of six cyclones, with three located on each pant-leg side. Accordingly, up to three FBHEs on each pant-leg side are used in order to perform additional heat duty. Lurgi also proposed a 500 MWe CFBC design for typical hard coals, which employs two parallel-arranged combustors with a convective pass in the middle. Each combustor has its own air and fuel/limestone feeding systems to ensure homogeneous fluidisation and is equipped with four solid separators and four associated FBHEs. The design thus results in a compact boiler (Wu, 2005).

Further scale-up of CFBC boilers to over 600 MWe is possible. Foster Wheeler together with a few European partners has launched a development programme to design a CFB boiler for 800 MWe. The design of the 800 MWe boiler will be based on the Lagisza design with the necessary scale-up modifications. The furnace will be enlarged, but still have one single fluidising grid with double-vortex compact separators arranged in parallel on both sides. A total of eight INTREX™ heat exchangers will be used to perform additional heat duty. This design is expected to increase the boiler efficiency to 93%, and the net plant efficiency will likely exceed 45% with steam conditions of 30 MPa/604°C/621°C and seawater cooling to 18°C (Wu, 2005). In China, a 600 MWe supercritical CFBC unit is under construction at the Baima site in Sichuan Province. The boiler is being developed jointly by Tsinghua University and Harbin Boiler Co Ltd, while the Dongfang Boiler Co and Shanghai Boiler Co are also involved. The boiler design features a pant-leg furnace based on Alstom's design, combined ignition systems both above and under bed, vertical tube water wall, six cyclones with six external heat exchangers, roller-type ash cooler and four regenerated air heaters (Mao, 2008). The boiler will adopt steam conditions of 25.4 MPa/571°C(±5°C)/569°C(±5°C) with a boiler efficiency of 91.9%. It is designed to be able operate at 30% MCR with out oil supply. The flue gas will meet the emissions requirements of $SO_2 \leqslant 400$ mg/m^3 and NOx $\leqslant 200$ mg/m$^{3.}$

It is noted that the superheat and reheat steam temperatures are increased moderately in the Lagisza SC CFBC boiler, although the superheat outlet pressure is increased dramatically. This reflects the development rationale behind the project, that is, to use currently approved materials based on ferritic/austenitic alloys, for which steam conditions up to 30 MPa and 600°C/620°C can be applied. Similarly to further development of USC PCC technology, a key to the successful development of further supercritical CFBC technology is the availability of high temperature metal materials. With the ongoing development in this area as discussed in Section 2.3, more advanced steam conditions will be possible in CFBC units in due course.

Although most CCS projects are for PCC units, there have been several projects proposed involving CFBC. The Hodonín project is one of the two post-combustion projects currently being considered in the Czech Republic. The Hodonín co-generation plant comprises two CFBC units (60 MW and 45 MW). Fuel is a combination of local lignite and biomass. An amine scrubber has been proposed with CO_2 being stored in depleted oil/gas reservoirs or deep sedimentary acquifers. A potential start-up date of 2015 has been suggested (Budinsky, 2008). The potential for applying oxyfuel firing to the Lagisza supercritical CFBC has been examined and modelled by Foster Wheeler. The Lagisza plant design was adopted as the reference case. Another recent development is the OXYCFB300 demonstration project pursued by Fundación Ciudad de la Energía (CIUDEN), an institution created by the Spanish Government. Foster Wheeler is involved as the main technology developer and will supply a 30 MWth CFBC test unit based on its Flexi-Burn™ technology, some auxiliary equipment and site advisory service. Flexi-Burn™ is in fact an oxyfuel combustion technology. The unit is expected to be operational by the second half of 2011 with testing programmes expected to follow shortly thereafter. The unit will be part of CIUDEN's Integrated CCS Technology Development Plant located near Endesea's Compostilla Power Plant in Ponferrada, Spain, and will be designed to test a wide range of domestic (anthracite) and imported coals as well as biomass, operating in both conventional and carbon capture mode. In December 2009, the OXYCFB300 project was selected as one of the EU's CCS demonstration plants. The project will proceed in two stages. During the first stage (2009-12), CIUDEN will develop and validate the oxyfuel CFB concept. It will also study the geological storage of CO_2 via an experimental plant in Hontomín, and in order to resolve associated technical issues, will construct a test unit for CO_2 transport. Endesa will carry out technical feasibility studies, analyse risks, and undertake the basic engineering for a 300 MWe demonstration plant. Endesa will also define and characterise suitable CO_2 storage locations for the demonstration plant and undertake the basic engineering for the pipeline infrastructure. During Phase II (2013-15), the partners will focus on the construction and operation of the 300 MWe plant and storage of up to 1 Mt/y of CO_2 (Endesa, 2010).

4 Gasification-based technologies

This chapter discusses gasification-based technologies for low quality coals, including IGCC, coal-to-liquids (liquid fuel or chemicals) and underground coal gasification. These technologies are relatively new and altogether account for just a small proportion of consumption of low quality coals. Nevertheless, coal gasification has the potential for greater products flexibility and improved operational economics. IGCC is widely considered as a new technical path for more efficient electricity generation while maintaining a near-zero environmental footprint. Coal-to-liquids (CTL) represents a significant high value market opportunity for relatively cheap coal, and, in many countries, can potentially contribute to their security of energy supply. Underground coal gasification (UCG) is widely regarded as an important technology to unlock vast amounts of energy in otherwise inaccessible coal deposits using currently available mining techniques, and can therefore increase the world's energy supply considerably. However, these technologies need to overcome many technical and economic challenges before they become commercially mature and widely deployable. To this end, a number of commercial or large-scale demonstration projects have been developed in respective technologies. Some of these projects involve the use of low quality coal, and will be discussed in some detail as follows.

4.1 IGCC

Integrated Gasification Combined Cycle (IGCC) is a high efficiency power generation technology, which comprises a Brayton cycle and a Rankine cycle. In the Brayton cycle, coal and/or other solid feedstocks are converted to synthetic gas (syngas) in a gasifier, which after cool cleaning of dusts and acid gases is burned in a high efficiency gas turbine. The exhaust gas from the gas turbine flows into a Heat Recovery Steam Generator (HRSG) to raise steam for the Rankine cycle. Typically, the Brayton cycle produces 60–65% of the total power, while the Rankine cycle contributes the rest (Rousaki and Couch, 2000; Barnes, 2009).

IGCC has attracted great interest from power producers because it has potentially many advantages compared to conventional PCC or CFBC power generation technology. First, IGCC has high thermal efficiency currently comparable to the best existing PCC plants and with potential for further increase. The highest reported efficiency for an IGCC is 41.8% (HHV) where a Shell gasifier fuelled with Pittsburgh coal powers an F-class turbine (Barnes, 2009). With improved and optimised design, this efficiency is estimated to increase to 44–45% net (HHV) (46–47% net, LHV). Second, IGCC has potentially very low environmental impact. Its high efficiency means low CO_2 emissions per unit of electricity produced. SO_2, NOx and particulates are reduced to low levels through deep cleaning of the syngas before firing in the gas turbine. In addition, elemental sulphur or sulphuric acid can be produced from the SO_2 removed, which is marketable and brings in revenue. Finally, IGCC uses much less water since the Rankine cycle produces only 35–40% of the total plant power output. Another reason for lower water consumption is the direct desulphurisation of the syngas. IGCC does not require flue gas desulphurisation that consumes large amounts of water. There are further gains in reduction of water use when CCS is incorporated compared to PCC/CCS or to CFBC/CCS systems.

IGCC can use any of the three types of gasifier: moving bed, fluidised bed and entrained flow. The choice of gasifier depends primarily on the characteristics of the coal to be used (*see* Table 5). The moving bed gasifier generally cannot cope with a very fine coal feed, and the syngas contains significant amounts of tars and other low molecular mass hydrocarbon species due to the countercurrent flowing pattern of gas and coal in the gasifier. These tars and hydrocarbon species need to be removed before firing the syngas in the gas turbine. Another limitation of moving bed gasification is the low throughput per unit; for example, the Lurgi design is limited to an output equivalent to 100 MWe. This limitation necessitates the use of multiple gasifiers in a commercial-

Table 5 Comparison of three types of gasifier (Taberer, 1998; Ratafia-Brown and others, 2002)

Gasifier type	Moving bed		Fluidised bed		Entrained flow
Bottom ash conditions	Dry	Slagging	Dry	Slagging	Slagging
Coal size	5–80 mm	5–80 mm	0.5–6 mm	0.5–6 mm	<100–250 mm
Preferred feedstock	lignite, reactive bituminous coal, anthracite, wastes; caking coal possibly acceptable	bituminous, anthracite, petcoke, wastes; caking coal accpetable	lignite, reactive bituminous, wastes; caking coal possibly acceptable	lignite, bituminous, petcoke, biomass, wastes; caking coal not acceptable	lignite, reactive bituminous coal, anthracite, petcoke; caking coal acceptable
Acceptability of coal fines	limited	better than dry-bottom	good	better than dry-bottom	unlimited
Ash content limits	no limits	<25% preferred	no limits	no limits	<25% preferred
Preferred ash fusion temperature	>1200°C	<1300°C	>100°C	>1100°C	<1300°C
Exit syngas temperature	425–650°C	425–650°C	925–1040°C	925–1040°C	1250–1600°C
Gasification pressure	3 MPa	3 MPa	0.1 MPa	0.1–3 MPa	up to 8.6 MPa
Oxidant requirement	low	low	moderate	moderate	high
Steam	high	low	moderate	moderate	low
Unit capacity range	10–350 MWth	10–350 MWth	100–700 MWth	20–150 MWth	up to 700 MWth
Key features	hydrocarbons (for example tars) in the raw syngas		multiple-time char recyle		high sensible heat in raw gas
Key technical issue	utilisation of coal fines and hydrocarbons		relatively low carbon conversion		raw gas cooling; warm gas cleaning

scale IGCC plant, thus increasing the capital costs. Consequently, large IGCC plants mostly use either fluidised bed or entrained flow gasifiers.

4.1.1 The impact of coal characteristics

Since IGCC comprises a number of integrated components, the impact of the characteristics of the coal to be used on all the components must be assessed in the design stage. Certain types of gasifier are more appropriate for certain types of coal, as indicated in Table 5. However, there is insufficient operational experience to draw firm conclusions on the impact of coal properties. Most of the currently operational demonstration plants were designed for high quality coals, with only five plants burning lignite or mixture of subbituminous coal and petcoke. However, there have been tests undertaken on these demonstration plants, which involve the use of low rank coal, biomass or wastes. Experience gained from these tests is of relevance to low quality coals.

The most significant ash property for a gasifier is the ash fusion temperature. In slagging gasifiers, coals with relatively low ash fusion temperature are the preferred feedstock. However, coals with high ash fusion temperature may still be used with the addition of a fluxing agent, usually limestone. The fluxing agent reduces slag viscosity and permits satisfactory slag discharge from the bottom of the gasifier. The amount of fluxing agent needed is proportional to the weight of the ash; more fluxing agent is required for coal with a higher ash content. In slagging gasifiers of either moving bed or entrained flow type, the preferred ash fusion temperature should be no more than 1500°C, and preferably less than 1300°C. For dry bottom moving bed gasifiers or fluidised bed gasifiers, it is necessary for the ash fusion temperature to be higher than 1200°C or 1100°C respectively. An important feature is that ash fusion and softening temperatures are lower under reducing conditions than in an oxidising atmosphere. As a consequence, ash may soften and become sticky at moderate temperatures in, for example, fluidised bed gasifiers. A low temperature in the reaction zone is therefore desirable. However, complete char conversion is difficult when the reaction temperature is too low. There is therefore a fine balance between the minimum temperature needed for high char conversion and the maximum temperature allowable for prevention of ash slagging/agglomeration. One method of avoiding the low char conversion at low temperature is to remove the char from the bed and burn it in a separate combustion unit. This, however, inevitably complicates the process and adds to the capital and maintenance costs.

Ash content is another concern for all types of gasifiers, determining, amongst other things, whether an oxygen-blown or an air-blown system is more suitable. High ash content coals are more suited to air-blown systems because large quantities of oxygen required would increase the cost of air separation considerably. Moreover, non-slagging processes are preferred because the more ash in the coal, the more energy is required to melt it. Air-blown moving bed or fluidised bed processes with dry ash removal are more suitable for high ash coals. However, operational experience of these processes using high ash content coals is limited, as the majority of operating IGCC demonstration plants are based on oxygen-blown entrained flow (slagging) gasification. Since gasification occurs at high temperature, there is sensible heat loss due to discharge of bottom ash or slag. A higher ash content means higher loss of sensible heat, although this may be only moderate, for example approximately 1–3% of total coal calorific value at 40% ash (db) in a range of ash discharge temperatures of 500–1400°C (Rousaki and Couch, 2000). The loss of sensible heat will become significant if a high ash content is combined with a high moisture content. A high ash content also means more consumption of fluxing agent in slagging gasification if the ash fusion temperatures are high. A high ash content has also been suggested to correlate with the unburnt carbon in fluidised bed gasification.

Ash behaviour in gasifiers is largely dependent upon the composition of the ash, the effects of which are still less well understood than in conventional combustion systems. Most importantly, elements such as Na, K, Cl, F, P and Pb vaporise during gasification and can form condensates on cold surfaces (particularly at 600–900°C). Since IGCC plants include an extensive network of heat exchangers downstream the gasifier, fouling/plugging is a very costly issue. For example, the syngas cooler has been one of the most troublesome parts of the plant. Since it is an expensive piece of equipment and difficult to engineer, there is a strong economic incentive to select coals with low contents of the above elements. Alkalis and chlorine are often abundant in low rank coals, so their use in IGCC plants require special consideration of heat exchange fouling issues. Ash composition also affects the slag formation and its viscosity, which are important for slagging gasification. For example, the silica ratio ($SiO_2/SiO_2+Fe_2O_3$+ CaO-MgO) is used to assess slag viscosity and fusion temperature for Australian coals (Patterson and Hurts, 1996). Caking and swelling characteristics of coal also depend on ash composition. Generally, non-caking coals are preferred, which tend to remain dispersed and to retain reactive surfaces at high temperatures. To accommodate caking coals or other feedstocks, some moving bed gasifiers incorporate stirrers in the bed or other modifications.

A serious issue relating to ash composition is the syngas cleaning. Volatile alkalis, chlorides and other impurities have to be removed from the syngas to protect the gas turbine blades from deposition and corrosion. In the current demonstration plants, the syngas exiting the gasifier needs to be cooled before it is cleaned. Gas cooling is achieved through the network of heat exchangers and, in some systems, also through quenching with recycled cooled syngas. Cool gas cleaning is well proven and extensively used in the petrochemical industry. However, cool cleaning has a great energy as cleaned syngas needs to be reheated before it enters the gas turbine. Cleaning of hot syngas is thus preferable, and another benefit is that condensation of the steam present in the syngas can be avoided. This steam can then be utilised downstream for hydrogen production when CO_2 capture is applied. 'Warm gas' cleaning technologies, for example those jointly developed by Research Triangle Institute and US NETL, are available and generally operate at around 150–400°C. Gas cleaning at even higher temperatures of around 500–600°C are still under development. Since even these temperatures are blow the temperatures of syngas at gasifier exit, some cooling is nevertheless still required. Warm gas cleaning is estimated to increase the plant efficiency by 2–3 percentage points for air-blown entrained flow gasification, and by 1–2 percentage points for oxygen-blown gasification (Klosek and others, 1994). Nevertheless, failures due to thermal stresses and ash deposition causing filter bridging and blinding have been experienced. Ash deposition and corrosion on the filter ceramic materials have special relevance to low rank coals.

Although gasification is generally insensitive to the S content in coal, an excessive S content will lead to increased corrosion on heat exchanger surfaces by H_2S and/or carbonyl sulphide (COS) formed during gasification. All currently operational IGCC plants use low temperature S recovery systems (typically the Claus process) that are capable of removing 99% of the sulphur. However, S recovery at high temperature will increase the overall plant efficiency. Recently, there has been a promising development in this regard: the High Temperature Desulphurisation System (HTDS) designed to remove sulphur from hot syngas and the Direct Sulphur Recovery Process (DSRP) that converts recovered sulphur compounds to pure sulphur. Both technologies are sponsored by US DOE's National Energy Technology Laboratory and Research Triangle Institute. HTDS has been tested for more than 3000 h on a GE quench gasifier fed with high S US eastern coal. Compared to a standard GE reference plant with Selexol for sulphur removal, HTDS yields an increase in overall thermal efficiency by 3.6% for a 600 MW IGCC plant. It could also reduce the capital cost of the plant by 269 $/KW and the electricity cost by 9.6% (US DOE, 2008). The S content is of special concern in fluidised bed gasification where limestone or other calcium-based sorbents are added to capture S in-bed. S capture by limestone requires a bed temperature in excess of 870°C for the in-bed calcination that produces an active lime sorbent. However, the presence of alkalis can cause agglomeration in the bed above this temperature range. Careful control of bed temperature is therefore necessary to achieve a good balance between effective in-bed sulphur capture (as well as acceptable carbon conversion) and prevention of bed agglomeration.

The nitrogen content in coal is not of concern because the fuel-bound N is converted to ammonia (NH_3) which is removed from syngas almost completely during the gas clean-up. NOx emissions from an IGCC plant originate solely from oxidation of molecular nitrogen (thermal NOx) in the gas turbine combustion chamber. With appropriate design of the chamber, thermal NOx emissions can be controlled to low levels.

Coal moisture content is a critical coal property for gasification processes, and has two major implications. First, similar to combustion processes, a high moisture content will lower the thermal efficiency of a gasification process because a significant portion of energy from the coal is used to evaporate the moisture. Feed coal is often dried prior to gasification using low grade heat, and high moisture content coals are generally not economically suitable for gasification. For instance, the IGCC plant at Schwarze Pumpe used pre-dried lignite, while at the Puertollano IGCC plant, despite the feed having just ~11% moisture, the coal/petcoke mixture is also pre-dried. A study in the USA found the economic moisture content of coal feed to be 5% for dry-feed entrained flow gasifiers and 10–20% for dry-feed fluidised bed gasifiers (Rousaki and Couch, 2000). There are extensive research efforts under way to develop less costly advanced drying processes (*see* Chapter 5). A high moisture content also presents difficulties associated with feeding coal into pressurised gasifiers. In dry-feed gasifiers, the feeding system is complicated with the use of lock hoppers. If a coal has a high moisture content, there may be coal bridging or hold-up problems in the lock hoppers. A slurry-feed system has a simple design and provides a more reliable and controllable feed rate than a dry-feed system. Since water is added to prepare the slurry, some energy from the coal has to be used to evaporate the water in the gasifier. Coals with high moisture content are thereby undesirable from the standpoint of plant efficiency.

Finally, high reactivity is a desirable coal property for gasification as it reduces the quantity of oxidant used and minimises the char recycling while achieving high coal conversion rates. Since gasification slows markedly when the bed temperature decreases, high reactivity is particularly important for moving bed and fluidised bed gasifications. Although there is no solid evidence of the effect of coal rank on reactivity, many low rank coals are found to have high reactivities. One of the reasons is the catalytic effect of metals and their oxides present in low rank coals. For instance, sodium, potassium and calcium have been found to be an important catalyst for oxidative gasification. When coals with relative low reactivities are used for gasification, some form of char recycling is necessary. The two-stage design for entrained flow gasification is also aimed at maximum carbon conversion.

4.1.2 Current experience

There are a limited number of coal-fired IGCC commercial demonstration plants in operation in the USA, Europe and Japan. The large ones include the Wabash River IGCC repowering project (262 MWe, E-gas™ gasifier, in Indiana, USA), the Tampa Electric Company IGCC project (250 MWe, GE (Texaco) gasifier, in Florida, USA), the Demkolec IGCC project (253 MWe, shell gasifier, in Buggenum, the Netherlands), the ELCOGAS project (335 MWe, Prenflo gasifier, in Puertollano, Spain), The Vresova IGCC plant (200 MWe, Lurgi gasifier, the Czech Republic) and the Nakoso IGCC project (250 MWe, MHI gasifier, in Iwaki city, Fukushima, Japan). Most of these plants, except the Puertollano and Vresova, are using bituminous coals as the fuel. Overall IGCC availability has increased in recent years and can exceed 80%; gasifier availability can exceed 90%. Very low atmospheric emissions have been produced, well below existing permitted levels in most countries. The European plants have a relatively higher degree of integration between the gas turbines and the air separation unit (ASU), which were designed for achieving higher plant efficiencies. However, this has entailed longer start-up times and compromised operational flexibility. Currently, there are five IGCC facilities that fire low rank coals or coals with wastes and petcoke. These facilities will be discussed as follows.

Vresova IGCC plant

The 400 MWe (gross) Vresova IGCC plant, operated by Sokolov Coal Corporation, is the only coal-based IGCC facility in the Czech Republic. It comprises two combined cycle units, each with a 128 MWe (net) GE 9E gas turbine and a 57 MWe ABB steam turbine (net). The primary fuel for the two gas turbines is the syngas produced in 26 old Lurgi type moving bed gasifiers, which consume around 2000 t/d of lignite and produce about 4.7 million m^3/d of raw syngas, and a 175 MWth Siemens entrained flow gasifier that fires liquid condensates (mainly coal tar) from the 26 moving bed gasifiers. Syngas contributes only around 70% of the plant's total electrical output, and natural gas is used as back-up fuel to meet peak load demand. The syngas input can be increased from 70% to 100% of its maximum contribution in only five minutes (Collot, 2002). The thermal efficiency of the gas turbines is 34.8% (net, LHV), while the overall combined cycle efficiency is 50.5% (net, LHV) (without district heating). Syngas is cleaned, in part, by a Rectisol process unit. Acid gases from the Rectisol unit are used to produce sulphuric acid in a wet sulphuric acid plant, added in 1993. In addition to electricity, the plant produces liquid by-products such as coal tar, phenol concentrate and liquid ammonia. Replacement of the moving bed gasifiers with more modern technology has been investigated; one of the options is the High Temperature Winkler (HTW) fluidised bed technology, although there has been no progress so far. Trials of cogasifying biomass and lignite are planned (Mills, 2010).

Sanghi IGCC plant

The 60 MW Sanghi cogeneration plant is the first commercial-scale IGCC facility in India. It was built by Ignifluid Boiler India Ltd (IBIL) Energy Systems to supply power and steam to Sanghi Industries' cement plant in the Kutch region of Gujarat State in India. Lignite is used as the main fuel. The project features a simplified air-blown, pressurised fluidised bed gasification technology developed by the Institute of Gas Technology (IGT) of Chicago, Illinois (now called U-gas) and further developed by Enviropower. The power island includes a 38 MW gas turbine, a 90 t/h heat recovery steam generator, and a 26 MW steam turbine. GE supplied the gas and steam turbines for the power island. IBIL fabricated the gasifier and the heat recovery steam generator. The plant provides peak power of 52.5 MW and an average of 30 MW to the cement plant. Surplus power is sold to the grid. It also supplies 40 t/h of steam to a captive desalinisation plant which provides process water to the cement plant and domestic water to the local community. The plant was commissioned in 2002, and is owned and operated by IBIL Energy Systems for the first ten years, after which ownership will be transferred to Sanghi Cement.

Schwarze Pumpe

The 74 MWe Schwarze Pumpe IGCC cogeneration plant near Dresden was owned by Sustec SVZ and had been in operation in Germany from 1997 to 2006. In addition to lignite, various wastes and biomass had been gasified, including demolition wood, used plastics, sewage sludge, auto-fluff, municipal solid wastes, waste oil, paint and varnish sludge, mixed solvents, tars, and on-site process wastes. There were three gasifiers of different design: an oxygen-blown FDV Lurgi rotating grate unit (2.5 MPa, 14 t/h), an oxygen-blown BGL slagging gasifier (2.5 MPa, 35 t/h) and an oxygen- blown GSP entrained flow gasifier (2.5 MPa, 130 MWth or15 t/h). An important concept at the site was the integration of several different types of gasifier, thus enabling a wide range of input materials to be used with local lignite. This plant was generally viewed as being more in competition with conventional incineration rather than power generation. It had both emissions and efficiency advantages over conventional refuse incinerators. Lignite was dried and briquetted and fed into the moving bed gasifiers together with waste pellets. The syngas was fired in a GE 6B gas turbine. In addition to electricity, the plant also produced 360 t/d methanol, but the product was stopped for economic reasons in 2006 (Higman, 2008). The BGL gasifier was subsequently disassembled and shipped to India, while the Lurgi gasifier was scrapped and the GSP entrained flow unit was sold to Siemens (Porsche, 2010).

Puertollano IGCC plant

ELCOGAS, a consortium of eight European utilities and three technology suppliers, built and commissioned a 335 MWe coal/petcoke-fuelled IGCC plant in Puertollano, Spain in 1998. The Puertollano IGCC plant uses a Krupps-Koppers PRENFLO single stage, oxygen-blown entrained flow gasifier with dry pulverised feed. The basic fuel is a local high ash (~40+%) subbituminous coal blended in equal proportion with high sulphur (5.5%) petcoke from the Puertollano REPSOL refinery. At full operational capacity, the plant consumes 700 kt/y of mixed fuel. Also, several trials have successfully cogasified meat and bone meal (1% and 4.5%) in 2001 and olive oil waste (1–4%) in 2007-09. The gasifier features four horizontally arranged burners and a reaction chamber encased by a membrane wall with an internal cooling system that raises pressurised steam. Gasification takes place at 1200–1600°C and under 2.5 MPa. The raw gas is cooled from ~1550°C to 235°C by direct cooled recycled gas quench and heat exchange through the membrane wall. The particulates are removed in a ceramic candle filter system operating at ~240°C. Part of the syngas is recycled for quenching the hot raw gas, and the remaining syngas is then cleaned of acid gas species using a venturi-type scrubber. The desulphurisation process comprises a COS hydrolysis reactor and the Claus sulphur recovery unit, which produces up to 3.1 t/h of >99.8% pure sulphur. Gas cleaning operations reduce H_2S levels in the raw gas from 0.83% to 3 ppmv, COS from 0.31% to 9 ppmv, and virtually eliminate HCN (Mills, 2006). The cleaned syngas is saturated with water and mixed with residual nitrogen before being fired in the gas turbine in order to minimise NOx formation; the nitrogen addition also results in increased gas turbine output. The combined cycle comprises a Siemens V 94.3 gas turbine with twin horizontal silo-type lateral combustion chambers and a two-casing Siemens K 30-16-1 subcritical steam turbine. The plant's target gross energy efficiency is 47% (LHV) under ISO conditions. Total gross electricity production at the plant showed a steady improvement from 1998 to 2002. But in 2003 and 2006, gas turbine problems were encountered and two major gas turbine overhauls were made, thereby reducing annual production. Also in 2006 major problems were encountered with the fly ash candle filter unit. Other main causes of reduction in power production were a gas turbine main generation transformer isolation fault in 2004-05 and a waste nitrogen compressor coupling fault in the ASU in 2007-08 (Coca and Carcía-Peña, 2010). Therefore, the average availability of the plant has still to be improved.

As a key part of Spain's national strategic research programme (PSE-CO2), a 14 MWth pilot plant was established in 2010 for testing of hydrogen production and CO_2 capture (Coca and Carcía-Peña, 2010). The test results will be provided to the Spanish government for evaluation, aimed at supporting further development of IGCC technology. The pilot plant takes 2% of the syngas from the existing IGCC plant, captures CO_2 from it and co-produces pure H_2. The pilot plant was constructed and commissioned in June 2010, and at the time of writing, operational tests are under way. The total project cost was €13 million, which suggests capture costs in the range of 18–22 €/tCO_2. ELCOGAS hopes that, following the current series of planned tests, capture costs can be reduced to approximately 10 €/tCO_2.

Morwell IDGCC pilot plant

The IDGCC (integrated drying gasification combined cycle)technology was specifically developed by HRL Ltd in Morwell, Victoria, Australia for the gasification of high moisture brown coals from the Latrobe Valley.

Figure 7 shows the schematic of the IDGCC process. Lignite is gasified in a fluidised bed gasifer, and the exiting hot flue gas is used to pre-dry incoming raw lignite in a direct contact entrained flow dryer. This configuration avoids the need for a separate dryer and high temperature heat exchangers for gas

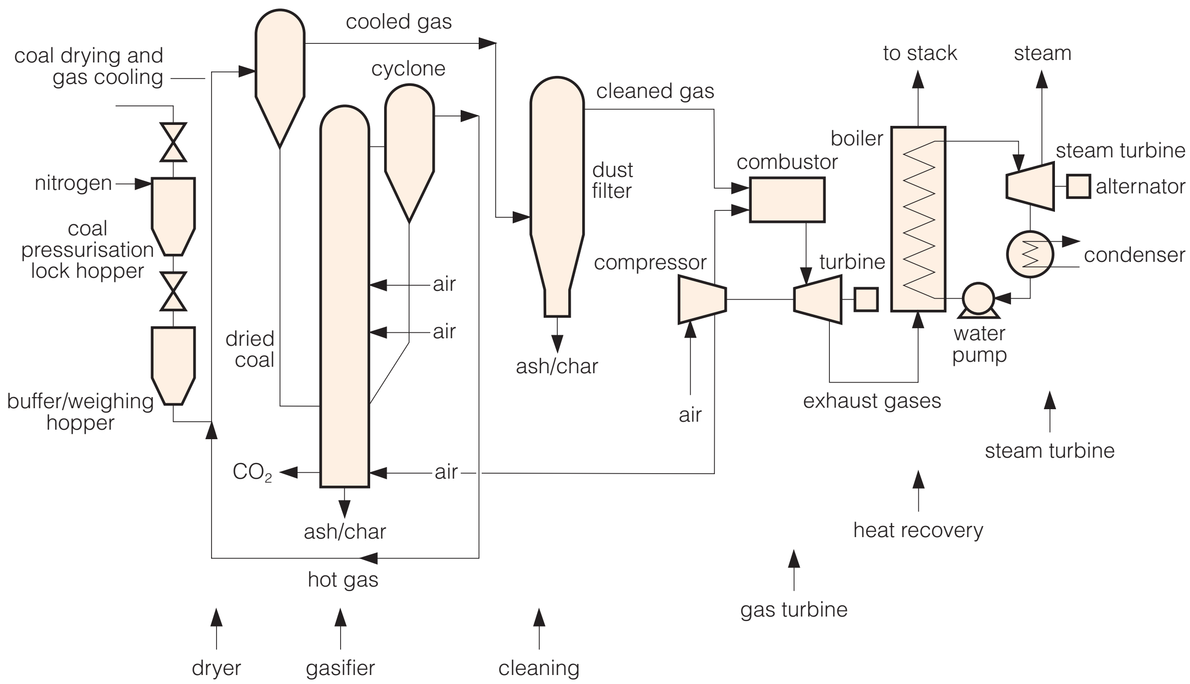

Figure 7 The schematic of IDGCC process

cooling, resulting in a cost saving. The gas from the gasifier goes through a dust filter and the cleaned gas is then burnt in a combined cycle to produce power.

The HRL technology provides a pathway towards the more efficient use of the vast coal resources in Victoria's Latrobe Valley. The major advantages of IDGCC include significant reduction in CO_2 and savings on water use. The IDGCC is believed to produce power with about 30% less CO_2 emissions than current Victorian best practise in brown coal power generation plants, due mainly to pre-drying of the moist brown coal before gasification (ETI, 2010). The large reduction in CO_2 is important to the future of power generation in the Latrobe Valley and vital to the Victorian Government's commitment to reducing greenhouse gas emissions from power generation. IDGCC also reduces cooling water by 50% (ETI, 2010). HRL also claims that this technology is suitable for pre-combustion CO_2 capture.

This technology has reached commercial demonstration stage following a 10 MW scale air-blown plant commissioned during the 1990s at Morwell in Australia. The plant included a 5 MWe gas turbine and generated electricity into the grid. HRL cites an efficiency of about 40% (HHV) without sulphur removal, compared to 28–29% (HHV) for conventional Australian lignite-fired PCC units. (Henderson and others, 2005). Tests with oxygen blowing have also been carried out using subbituminous coal at 300 kg scale under 1 MPa.

Dual Gas Pty Ltd has been established by HRL to build a proposed 600 MW IDGCC demonstration power plant at Morwell in the Latrobe Valley region (ETI, 2010). This commercial-scale project is expected to cost around A$1 billion and is designed to prepare the IDGCC technology for commerical deployment locally and potentially internationally. HRL has signed an engineer, procure and construct (EPC) contract with China National Electrical Equipment Company (CNEEC). The Victorian Government and the Australian Federal Government have committed A$150 million to the demonstration project. The Victorian Government has committed A$50 million to the project as part of its Energy Technology Innovation Strategy (ETI, 2010), a major component of the state government's response to climate change. Leveraging from the ETI grant, HRL obtained a further A$100 million from the Australian Federal Government's Low Emissions Technology Demonstration Fund (LETDF) for the construction of the new demonstration power plant. The plant will be built to enable the potential retrofit of CO_2 capture technology, when commercially viable. Planned to be operational by 2013, the new power station will be smaller in physical size than current conventional brown coal power stations of similar generation capacity.

It can be seen that experience with IGCC fuelled by low rank coal is very limited. Even for the existing plants, the driving forces for their construction are also very different. At Vresova and Schwarze Pumpe, the initial motivation was to add combined cycles to existing gasifiers to produce electricity and steam while achieving good environmental compliance. The Sanghi plant was not a power generation project, because its prime objective was to provide steam and electricity to the cement plant. Strictly, only the Puertollano and Morwell projects were dedicated to demonstration and development of IGCC for power generation. With regard to gasification technology, currently moving bed and fluidised bed gasifiers are more widely used as they are more suitable for low rank coals.

TRIG™ IGCC projects

A gasification process technology, called Transport Integrated Gasification (TRIG™), was developed by Southern Company, KBR and the US DOE for utilising inexpensive, low grade feedstock such as lignites, subbituminous coals and high ash coals. The TRIG™ system is an advanced air-blown dry bottom circulating fluidised bed gasifier that is designed to operate at high solids circulation rates and gas velocities, resulting in higher throughput, carbon conversion and efficiency. This technology has been tested at US DOE's Power Systems Development Facility at a scale similar to that of Morwell IDGCC pilot plant. A 582 MWe TRIG™ IGCC plant that will fire a Mississippi lignite has now been permitted and under construction in Kemper County, Mississipi, USA. Start-up is scheduled for the third quarter of 2013 with commercial operation in 2014. The plant will also feature 65% CCS. In addition, a 120 MWe TRIG™ IGCC is being built in Guangdong Province, China which is scheduled to begin operation in 2011. At this TMEP (Dongguan Tianming Electric Power Co Ltd) plant, a TRIG™ gasifier is added to an existing gas turbine combined cycle so that the plant can use syngas from coal to generate electricity (US DOE, 2011).

4.1.3 Future development

Table 6 summarises the newly planned or proposed IGCC projects relating to the use of low quality coal. Low quality coals are likely to figure prominently in future generation capacity. This is because

Table 6 The planned or proposed IGCC project firing on low quality coal

Project/plant	Country	Output capacity	Comments
The Maritsa East 4 plant	Bulgaria	~600 MW	Proposed; lignite
Low Energy Lignite Project	Bulgaria	400–600 MW	Proposed; lignite; CCS incorporated
The Goldenbergwerk plant	Germany	450 MW (gross)	Planned, but put on hold in late 2009; Rhenish lignite, and pre-dried using the WTA process; about 90% CO_2 capture and deep saline formation storage; a 1000 MWth entrained flow quench gasification operating at 40 MPa pressure is proposed; developed by RWE AG together with BASF and the Linde Group
Mesaba Energy project (Excelsior Energy)	USA	600 MW	In permitting stage with proposed start-up in 2014; subbituminous PRB coal and bituminous coal, and blends of subbituminous and petcoke; ConocoPhillips E-Gas gasification technology with two trains; amine scrubbing for CO_2 capture and used for EOR
Mississippi Power and Southern Company	USA	600 MW	Proposed, start-up 2013-16; local lignite; air-blown transport gasifier; CO_2 capture for EOR in Mississippi oilfields
Luminant	USA	2 x 630 MW	Proposed, PRB subbituminous coal and lignite
Wallula Resource Recovery	USA	915 MW	In permitting stage, proposed start-up in 2013; PRB subbituminous coal
The Monash project	Australia	160 MW	Plans placed on hold in December 2008; to incorporate coal-to-liquids and CCS activities; Latrobe Valley brown coal
HRL's IDGCC demonstration project	Australia	600 MW	Construction planned to commence in 2011; expected to come online in 2013; will be built to enable the potential retrofit of CO_2 capture technology, when commercially viable
The Dodds-Roundhill project (Sherritt International)	Canada	Initially hydrogen and SNG production, may include IGCC later	Feasibility study completed, and phased construction from 2010 to 2012; local subbituminous coal; 4 Siemens SFG 500 gasifier; 92% CO_2 capture for EOR
Vijayawada commercial demonstration project (BHEL & APGENCO)	India	125 MW	Initial construction began in July 2008; high ash (typically 42%) Indian coal; BHEL air-blown pressurised fluidised bed gasifier

experience with these fuels in conventional gasification systems is extensive, and their use in IGCC with efficient pre-drying is a logical extension of the technology. Entrained flow gasifiers will be the most common installation in future IGCC plants. Gas turbine development will continue to be based on natural gas requirements, with H-technology becoming increasingly used with concomitant economies of scale. There may be the possibility of one-to-one matching of gasifier to turbine if the gasifier unit size evolves. This will reduce complexity and increase economies of scale. Cryogenic separation will still be the main oxygen production technology. However, ion transport membranes look promising in the longer term. Carbon capture and storage systems are likely to be based on current familiar technologies; for example, the water gas shift reaction and subsequent chemical scrubbing approach. Partial capture will be more practical in the first generation IGCC/CCS units, followed by higher rates of capture up to or exceeding 90%.

4.2 Coal-to-liquids

Coal-to-liquids (CTL) includes conversion of coal to liquid fuels or chemicals. Although this is not traditionally a main use of coal, considerable interest in this application has arisen in recent years due to concerns over security of oil and oil products supply on the international market and increasing price volatility. There are two major conversion process routes, namely, direct liquefaction and indirect liquefaction. In direct liquefaction, solvents consisting mainly of recycled material are used to break down, with the help of catalysts, the complex molecular structure of coal at high temperature and pressure, usually in the presence of hydrogen. This is to maximise the yield of the smaller molecules needed to produce distillable liquids that can be used as transport fuels. The products are heavily dependent on the molecular structure of the coal being used as well as the process operating conditions. The products from direct coal liquefaction tend to be highly aromatic, thus making them difficult to use as high quality transport fuels, although they can be rich in octane aromatics and therefore a good gasoline substitute. Indirect coal liquefaction involves coal gasification to produce syngas, cleaning and purifying of syngas, and Fischer-Tropsch (FT) synthesis or methanol synthesis. The FT synthesis produces mainly diesel and some gasoline, while the main fuel product of methanol synthesis is gasoline and, in some cases, dimethylether (DME).

4.2.1 The impact of coal characteristics

Coal properties and characteristics have wider implications for coal liquefaction than for combustion as the process is more complex. Coal type, the structural chemistry of coal, and the mineral matter have significant effects on the liquefaction process and the liquids produced. These effects are more pronounced on direct liquefaction than on indirect liquefaction in terms of the nature of the liquid products. Since indirect liquefaction is based on the synthesis of syngas, the product has a higher degree of homogeneity and consistency. Also the effects of coal properties and characteristics on indirect liquefaction are largely limited to the gasification process, which has been discussed in Section 4.1. Once the syngas has been produced, downstream processing does not depend on the coal characteristics. The composition of the syngas product depends on whether the gasifier is oxygen- or air-blown, the amount of steam used, the temperature and pressure in the gasifier and the coal used. A detailed discussion on the effect on syngas quality of coal characteristics and gasifier type can be found in a previous IEA CCC report (Couch, 2008).

The behaviour of coal during direct liquefaction is governed by coal rank, petrographic composition and the mineral matter present. Generally, the aromaticity of coal's organic structure increases with coal rank, featuring a growth in the abundance of large complex carbon ring systems. Also, the presence and importance of oxygen functional groups decrease in higher rank coals. With increasing rank, there is a transition in crosslink type from hydrogen bonds to ether and aliphatic links to less-reactive biphenyl bonds. As a result, higher rank coals tend to have lower reactivities in direct liquefaction. A compromise between the over-reactivity of the low rank coals and the un-reactivity of the highest rank coals made the high volatile bituminous coals the optimum direct liquefaction feedstock. However, rank is only one indicator of the molecular structure of a deposit. The experience of much of the work reported on direct coal liquefaction points to the fact that many subbituminous coals can provide a suitable feedstock.

For bituminous coals, a strong correlation appears to exist between the liquefaction and their coking properties. The liquefaction behaviour of subbituminous coals and lignites differs from that of bituminous coals. Lignites tend to be more readily converted in moist mixtures of CO and H_2 rather than in hydrogen alone. Low rank coals convert more slowly and incompletely than bituminous coals. They are more sensitive to solvent H-donor concentration, and require more severe reaction conditions to maximise yield. Although the total liquid yield tends to decrease with decreasing rank, the proportion of low-boiling distillates increases. The liquefaction of low rank coals has caused problems because of the high viscosity of some of the residual products. This can sometimes be mitigated by increasing the liquefaction residence time, or by disposable catalyst addition. Another possible problem is the formation of calcium carbonate deposits. Low rank coals can contain up to 3% (by weight) of calcium, largely present as humic acid salts. The liquefaction process liberates calcium oxide, which reacts with CO_2 to form $CaCO_3$. Accumulation can be mitigated by the periodic removal of solids, or by pre-treating the coal with SO_2 so that the calcium preferentially forms $CaSO_4$. Liquefaction behaviour of coal can be adversely affected by coal oxidation after mining, particularly in low rank coals, due to natural weathering or ageing, or during drying. Oxidation introduces more ether, carbonyl, carboxyl and phenolic groups, and results in the loss of aliphatic structures. The liquefaction yield is thereby reduced.

4.2.2 Current experience and development

Interest in CTL is centred in three key countries which all have large coal reserves but have limited reserves of oil and/or gas, namely China, India and the USA. There are also considerable interest in countries as diverse as Australia, Botswana, Germany, Indonesia, Mongolia, the Philippines, South Africa and the UK. Japan, considering the security of its energy supply and the market potential for technology export, has also carried out extensive research and development work in coal liquefaction.

The world's main CTL production capacity is located in South Africa. Based on indirect coal liquefaction and the Lurgi moving bed dry bottom gasifier technology, Sasol now has 97 gasification units in total, which gasify 30 Mt/y high ash South African coals and produce 150,000 bbl/d of liquid fuels (that accounts for 30% of South Africa's total liquid fuel consumption). Sasol is considering the addition of another 80,000 bbl/d production capacity at its Secunda production site.

A more recent development is China's Shenhua 1 Mt DCL (direct coal liquefaction) demonstration plant that started operation in December 2008. This DCL plant is capable of producing diesel (715 kt/y), naphtha (250 kt/y), LPG (100 kt/y) and phenol (3600 t/y) using low ash subbituminous coal (LHV 24–26 MJ/kg). Shenhua aims to expand its DCL production capacity to 3 Mt. Shenhua is also collaborating with Sasol to construct an ICL (indirect coal liquifaction) demonstration plant with 80,000 bbl/d output capacity in Ningxia Province, China. It is noted that Shenhua's DCL and ICL projects are the only two commercial CTL projects approved by the NDRC after the Chinese Government acted to rein back the hectic R&D activities across the country. In addition, another three 160 kt/y ICL demonstration plants have been commissioned by Shenhua, Lu'an Group and Yitai Group In 2009. Yankuang Group also commissioned an ICL pilot plant in Shangdong Province with a capacity for producing 5000 t/y liquid products in 2004.

The Great Plains gasification plant is the largest coal gasification facility in the USA. The plant is located in Beulah, North Dakota, USA, and comprises dry bottom moving bed gasifiers firing lignites and two 450 MWe power generation units that consume the lignite fines. The main product is 3.5 million m^3/d synthetic natural gas (SNG), together with a range of by-products including naphtha, phenol, methane, anhydrous ammonia and liquid nitrogen, which help improve the plant economics. The plant consumes some 30 kt/d of lignite, more than half of which is gasified and the remainder is fired for power generation. The plant also supplies 75% of the CO_2 produced to the Weyburn oilfield for EOR; in order to meet a requirement for a steady and consistent supply, only part of the CO_2. is sold.

A number of R&D projects have been carried out on both direct and indirect coal liquefaction technologies with the support from the US government in the 1980s through to mid-1990s. Those efforts led to successful pilot plant operations and resulted in more efficient processes, improved catalysts and reactors, improved product quality and lowered product costs. One important outcome of the US work was to demonstrate that DCL could be applied to a wide range of coals and in particular, to the large reserves of low rank coals in the Powder River Basin. For instance, HRI's H-Coal® process was able to use Wyodak subbituminous coals as feed stock in its 200 t/d pilot plant in Catlettsburg to produce syncrude or fuel oil. The coal liquefaction R&D spree stopped in the late 1990s because the perception then was that any CTL process would be uneconomic compared to the use of oil-derived fuels. In recent years, the interests in CTL revived due to USA's desire to wean itself off imported oil. There are currently 13 CTL projects under consideration in the USA and at least five will use lignite or subbituminous coals as feedstock. Most of these are at the stage of feasibility assessment; more projects may be proposed between 2010 and 2015 depending on the incentives and support from governments.

Australia is also pursuing intensively the development of CTL technologies. Anglo America and the Shell Group have formed an alliance to develop the Monash Energy CTL project near the Loy Yang power station. The project, currently in an extended concept phase, envisages an integrated CTL operation that comprises a brown coal mine, a drying and gasification plant, carbon dioxide capture and storage and a FT plant for the production of transport fuels. Plant commissioning is targeted for 2016, but further assessments based on clarification of the plant design details and the practicalities of geosequestration of carbon dioxide are needed. At Salmon Gums in Western Australia, Spitfire plans to develop an opencast mine and CTL processing plant to extract oil and distillate products, mainly for the Kalgoorlie district. This 3.5 Mt/y operation is planned to produce about 270 million litres of oil products per year over an initial 10-year mine life. Hybrid Energy is planning to commence its FutureGas Project with the development of a surface lignite mine and construction of both a CTL conversion facility and a low-emission power generation plant at Kingston in South Australia. Carbon dioxide will also be captured from the FutureGas Project, and transported and stored. The exact timing of the Project will be determined following the completion of the current feasibility studies and subsequent FutureGas Environmental Impact Statement. Linc Energy Limited has commissioned its Chinchilla 5–10 bbl/d UCG-CTL PDU plant in 2009 to demonstrate that conventionally unmineable coal deposits can be tapped into through UCG to produce syngas and subsequently to produce liquid fuels via the FT process. Linc Energy is working to further improve the catalyst reduction system and intends to raise funds to build a 20,000 bbl/d commercial plant.

Although Japan has few coal reserves, it has pursued a substantial programme during the 1980s and 1990s to develop CTL technologies. Part of the reason for this was the perception that the stable supply of energy from surrounding Asian countries to Japan makes a significant contribution to its energy security (NEDO, 2006). Japan's Sunshine Project has led to a 150 t/d DCL pilot plant (NEDOL process) to process both bituminous and subbituminous coals at Kumamoto in Japan from 1996 to 1998. There was another 50 t/d DCL pilot plant operating on brown coal in Victoria, Australia from 1987 to 1990. NEDO is also looking to collaborate on coal liquefaction projects in Indonesia.

There is also a lignite-fuelled CTL project under development in Germany. The Schwarze Pumpe CTL plant is a joint venture between Syntroleum Corporation and Sustec, and has a planned total output capacity of 3000 bbl/d. This joint project is the first phase of a possible 20,000 bbl/d CTL project, which includes an expansion of Sustec's existing gasification capacity using GSP technology. Sustec also intends to expand its methanol production and power plant at Schwarze Pumpe (Syntroleum, 2006).

All the current or proposed projects are effectively demonstration plants, which are necessary before any large-scale investment in CTL plants is undertaken. CTL plants are likely to be sited, initially, near low-cost coal mines, where there is also adequate cooling water, and should be close to a CO_2 storage/sequestration site. For both CTL plants and those designed for polygeneration, the integration of CCS capability will become of increasing importance. Long-term government support is necessary because the capital cost of a CTL plant is significant and the product price may be subject to large variations. Also because of the high capital costs involved, it is quite difficult for current CTL plants to meet environmental requirements, which nevertheless have to be carefully addressed for any commercial development at large scale. It will only be possible to assess the contribution that CTL is likely to make in the longer term when operational results have been obtained and lessons have been learned from the first group of demonstration plants. This is unlikely to be before 2012, or might be as late as 2015, as the newly-built demonstration plants need to run for two or three years to resolve teething problems and to optimise operation. Meanwhile, the schedules for various feasibility studies may be extended in order to get the necessary information to justify any financial investment.

It should be noted that there are several important constraints to large-scale CTL development. The most prominent one is the resource constraint. There will be economies of scale and cost reductions associated with building and operating an increasing number of CTL plants. However, rapid large-scale development will place significant pressure on the supply of both coal and water resources; new coal mines may be needed and the cost of raw materials is likely to rise. China for example, already produced 2.97 Gt and consumed 3.09 Gt of coal in 2009 (Coal Information, 2010). Given the proven recoverable reserve figure of 115 Gt, this means that the R/P ratio is only just 39 years. If a substantial CTL programme requires an extra 0.5 Gt/y, then the R/P ratio will drop to 33 years, and unless exploration reveals currently unknown reserves, coal would be regarded as an increasingly scarce resource in only a few years time.

The view expressed by the IEA in *World Energy Outlook 2010* is that CTL emerges as an important growth sector, with demand increasing by around 125 Mtce (equivalent to 45% of the growth in global industrial coal use) as just over 1 million barrels per day or 1% of global oil demand by 2035 in the New Policies Scenario is obtained through CTL.

4.3 UCG

Underground Coal Gasification (UCG) has the potential to unlock vast amounts of energy in coal deposits that are inaccessible or uneconomic to explore using currently available mining technologies. If successful, UCG would substantially increase the proportion of the world's coal resources that could be classified as recoverable. UCG involves an injection borehole, through which air or oxygen (and possibly steam) are injected, and a production well from which product gas (mainly hydrogen and carbon monoxide) is drawn to the surface for treatment and use. The boreholes are linked by a zone through the coal seam where coal combustion and gasification take place in a continuously changing combustion zone that must be monitored and controlled. Commercial-scale operation would involve multiple wells. The technology has a long history in the Former Soviet Union, where it was carried out on an allegedly industrial scale. Trials have also taken place in the USA, Europe and China. Despite these trials and considerable amounts of research activities, no UCG projects have yet been demonstrated on a commercial scale. There are formidable technical obstacles to be overcome and regulatory issues to be addressed before this is possible. Many of these obstacles and issues are associated with the control of the underground reactor, which requires integration of knowledge from different disciplines so that the reactor can be designed with confidence and will be performing as intended. The Australian developments, along with the Majuba project in South Africa, are more advanced than other projects elsewhere. The first commercial-scale UCG operation is likely in the late phase of the next ten years (Couch, 2009).

Recent pilot-scale tests in Australia, Canada, China and South Africa have built on developments in directional drilling and computer modelling. These have been in different types of coal, at different depth and using various techniques for linking the injection and production wells. Results from current pilot projects are sketchy because some knowledge is proprietary. For instance, little is yet publicly known about what happens to the surrounding geology and hydrogeology when a combustion zone at 1000°C moves through a deep coal seam. The operations established in these tests fall well short of what are required for cost and environmental performance of commercially viable plants. Only some 15 to 20 Mt of coal have been gasified underground to date, which illustrates the limited experience with UCG. Further more, no trials have been made in thicker seams at any depth blow 300 m, except one that is now under way in a seam of modest thickness at a depth of 1400 m in Alberta, Canada (Couch, 2009). As the depth increases, drilling costs increases, and the in-seam underground reactor becomes less reliable and more difficult to control.

Tests have shown that, given the right conditions, coals of different rank can be gasified underground in principle. However, the behaviour of coal, its ignitability for example, will vary. Much of current testing work taking place in Australia, both at the Bloodwood Creek and Chinchilla, and at Majuba in South Africa uses subbituminous or high volatile bituminous coals. In Wyoming, USA, where much of the previous testing work was undertaken and future development is planned, subbituminous coals are used. Most recently, Pakistan was reported to complete a pilot UCG plant that will produce electricity using its Thar coal (lignite) reserves (APP, 2011). The lower rank coals are generally more permeable than higher rank coals, which implies it may be easier to establish linkage between boreholes. However, as low rank coals are softer, the strength of in-seam boreholes may be lower. More testing is necessary before a wide range of coals can be exploited through UCG. It is understandable that current pilot-sale trials are being undertaken in relatively favourable circumstances in terms of seam depth, thickness and coal ranks and characteristics. UCG project developers need to consider how to move quickly from pilot projects at carefully chosen and favourable sites to more ambitious demonstration projects that can provide the design basis for large commercial projects in a wide range of coal types and situations. Co-operation between developers and government-supported R&D facilities could expedite progress and increase confidence in the UCG technology.

5 Drying of low quality coals

It is known from previous chapters that low quality coals have an important role to play in providing affordable and abundant energy supply. However, currently, their utilisation is constrained due to a number of undesirable characteristics such as high moisture content. Low quality coals typically have high moisture contents in the range of 30–70% on a dry basis (Nunes, 2009). Without pre-combustion drying, approximately one quarter of the energy in the coal is used to evaporate the water present before any useful energy can be obtained. This leads to reduced thermal efficiency and higher emissions of CO_2 per unit of useful energy output. A high moisture content critically impacts on virtually every facet of utilisation of low quality coal. Drying of low quality coal prior to combustion is therefore important.

However, it is difficult to dry low rank coal efficiently. While most of the moisture (called free moisture) is present on the surface of bituminous coal, a low rank coal differs from a bituminous coal in that a considerable proportion of the moisture is held in the capillary pores. Figure 8 shows the forms of moisture in coal particles and the corresponding difficulties of removal. Allardice (1991) found that 20% of the water in a Victorian brown coal is bound more strongly than the other 80% for which the heat of desorption is simply the latent heat of evaporation. It is known that the hydrogen bonds are abundant and tend to distribute among fine pores in this particular type of low rank coal. Hydrogen bonding increases the strength of moisture holding, thus producing different evaporative behaviour during the course of drying. A comprehensive description of moisture and hydrogen bonds in Victorian brown coal can be found in Li (2004).

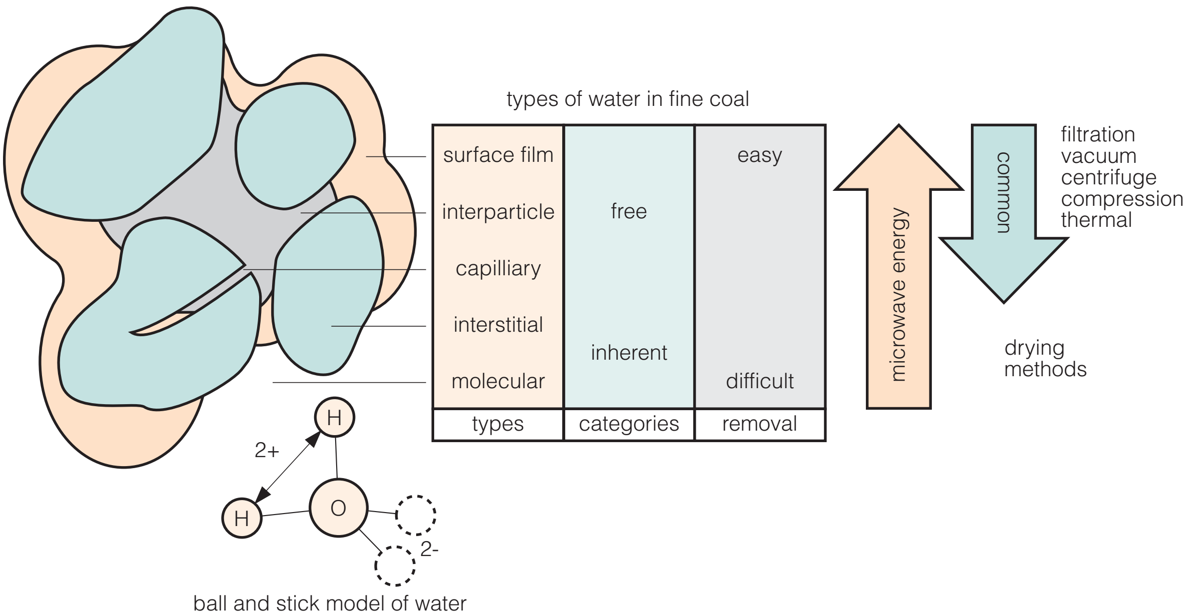

Figure 8 The various forms of moisture contained in coal particles (Graham, 2008)

There is a variety of processes in use or under development for drying low rank coal, which can be classified broadly into either evaporative or non-evaporative processes. Table 7 summarises the status, key features and the capacity range of those processes. In evaporative drying, the moisture removal is achieved in vapour form by applying heat to coal, either directly or indirectly. Not only is there latent heat (approximately 2.4 MJ/kg for water) involved, but 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 3.0–4.5 MJ/kg of water removed (Couch, 1990). The energy penalty for non-evaporative processes is generally less severe, typically between 1.0–2.5 MJ/kg of water removed (Couch, 1990).

Table 7 Various drying technologies and their status of maturity, capacity range and specific features

Process	Status of the technology	Capacity range	Features
Evaporative processes			
Indirect evaporative drying			
Steam tube drying (for example, NOAIR dryer)	Established and widely used in briquetting plants	Variable	Crushed coal feed (–6 mm); indirect evaporative process using a shell and tube heat exchanger; energy requirement 2.9–3.6 MJ/kg of water removed; product yield >95% if the low pressure steam is supplied from an adjacent power station
Direct evaporative drying			
Flash mill drying	Established and widely applied in conventional lignite-fired power stations	Dependent upon the capacity of coal mills; a large coal mill can has a processing capacity >200 t/h	Crushed coal feed (–30 mm); Product yield of approximately 75%; stand-alone process or as an integrated part in PCC boiler power stations;energy requirement about 3.4 MJ/kg of water removed, dried product has a moisture content of typically 2–17%; mill fires are the major concern, so the oxygen levels in coal mills need to be carefully monitor on a continuous basis
Rotary drum drying	Established and had been widely used in briquetting or grinding plants; rarely used at present due to the potential for exploration	Variable	Crushed coal feed (6–12 mm), dried product (–6mm) with a moisture content of typically 13–20%. Product yield of approximately 75%; energy requirement about 4.2 MJ/kg of water removed; adjustable residence time in the drum; high risk of dust explosion; flexible turn-down of throughput
WTA (steam fluidised bed pre-drying with internal heat utilisation)	Successful commercial-scale demonstration finished and being commercialised by RWE (Germany) through the Hazelwood 2030 project in Australia	An open cycle WTA system with maximum capacity of 210 t/h (raw coal) or 110 t/h dry product at RWE's Niederaussem K power plant	Effectively overcome the risk of fires and dust explosion using superheated steam (120–50ºC) as the fluidising medium; open or close cycle modes available; improve the thermal efficiency of a power plant by >4% due to heat recovery through recompression of the vapour from coal; grain coal feed (–2 mm) and the output > 90% (-1 mm) with a moisture content of 12%; coal residence time typically 60–90 min; virtually no cost increase compared to raw lignite-fired power plants due to savings in coal bunkers, beater wheel mills, flue gas recirculation and cleaning
IDGCC (integrated coal drying with gasification combined cycle)	A 10 MW air-blown pilot plant commissioned at Morwell, Australia; a commercial-scale 400 MW demonstration plant currently underway at Loy Yang Power Station, Australia	400 MW	Incoming raw coal is dried by recirculating hot flue gas from gasifers, thus saving 50% of cooling water compared to conventional boilers; the evaporated moisture is used to drive the steam turbine, so provides additional power generation from the steam turbine; compared to a typical supercritical boiler plant, overall thermal efficiency of IDGCC at about 40% (HHV) compared with 33% for the former, significant cut in CO2 emission by around 30% and estimated cost reduction of around 30%; suitable for pre-combustion CO_2 capture for near-zero emissions power generation

DryFining™ (low temperature fluidised bed drying)	Full-scale commercial demonstration now underway at the Unit 2 (546 MW) of the Coal Creek Station, North Dakota, USA	up to 122 t/h	Use the otherwise wasted heat from boiler flue gas to remove moisture from coal; a prototype dryer in the Coal Creek Station reduced the moisture content from as-mined 38.5% to about 29.5%; test results from the prototype dryer indicated an 0.3% increase in the boiler efficiency, a 0.9% fall in CO_2 emission, and a 3.5% decrease in pulveriser power consumption; SOx, NOx and mercury emissions also fell
Superheated steam drying			
SHS (Drying Solutions)	Commercially applicable to many substances, now being adapted on coal	N/A	Use superheated steam (135–538°C) for drying at atmospheric pressure; benefits include reduced coal degradation, higher process temperature (hence greater efficiency), reduced air discharge and elimination of risks of fires or explosions
SSD™ (GEA Process Engineering)	Commercially applicable to many substances, now being adapted on coal	N/A	The wet solids are dried as they flow along with pressurised transport steam in a closed loop pneumatic conveying type dryer; the transport steam (<1 MPa) is superheated indirectly in a tubular heat exchanger by medium pressure steam, flue gases or thermal oil; solid residence time is short (5–60 s), so fast drying is achieved; a second superheater may be used to achieve the required dryness; primary energy consumption is 2.7 MJ/kg evaporated water without any heat recovery; 70–90% of the energy is recoverable by re-using generated steam for heating purposes or through Mechanical Vapor Recompression; the absence of oxygen eliminates the risks of fires or dust explosion; no considerable emissions into the atmosphere
High velocity air flow grinding/drying			
DevourX mill	Commercial demonstration (150 t/h)	25–250 t/h throughput capacity	DevourX mill is a vortex-based machine that is capable of grinding and drying coal simultaneously at high throughput rates; it uses high-velocity sound and pressure to shatter solid materials and break the cellular structure to liberate the colloidal moisture contained within the cells; the DevourX mill also has low processing and maintenance costs
Alligrator Mills	Commercially applicable to agricultural goods, now being adapted on coal	design for three mill sizes: 0.15 t/h, 1.5 t/h, 3 t/h	Alligrator mill is a high-speed, wind-swept impactor with only one moving part; reduction in size is achieved within an artifically induced vortex by material to material impact with hammer speeds of 100 m/s, accelerated particle speeds of up to 200 m/s, and an adjustable anvil
LamiFlo™ (LF Pumping Ltd)	An industrial-scale test at 250 t/h in the USA	bespoke design of size up to 500 t/h of raw material; the Mobile LamiFlo™ Unit has a single unit capacity up to 250 t/h	LamiFlo™ is an integrated electricity-driven process for material pumping, drying and air classification; has been tested on 80 differing material types including coal and lignites; using no heating but air drying at very high mass flow rates, fast drying with typically 3 s residence time in the system; removes mainly the surface moisture and some of the inherent moisture under increased pressure; the feed particle size distribution affects the drying results

Table 7 Continued

Process	Status of the technology	Capacity range	Features
Brown coal densification and drying			
Coldry™ (Environmental Clean Technologies Ltd)	Pilot-scale demonstration from 2004 to 2007, Victoria, Australia	10,000 t/y pilot plant of processed coal	Moisture is expelled from the coal by means of attrition; the expelled water can be recovered for re-use; the processed coal is subsequently dried (around 40°C) using low grade waste heat from an adjacent power plant; the final product is in the form of densified pellets with energy value similar to many black coals; the product is stable, easily stored and transportable
LLD process (La Trobe Lignite Developments)	Batch-process pilot-scale 0.5 t/h demonstration; a 25 t/h Test&Development Plant now under developement	design for 25 t/h finished	The process is capable of producing 4 different dry carbon products: PacCarb®, PacChar®, ParCharCo® and PacAtCarb®; it also enables the recovery of all the bound and surface moisture from the brown coal, which has been found to be suitable for direct agricultural and industrial use; tars and other light hydrocarbon components produced during the drying and carbonisation processes can be fired in gas turbine to generate electricity
Microwave-based drying processes			
CoalTek (CoalTek Inc, Georgia, USA)	Technically proven at commercial scale	a 15 t/h commercial-scale demonstration plant in Kentucky, USA	Applicable to thermal and metallurgical coals; a low temperature, continuous process developed in modular manner; capable of removing surface, subsurface and bound water; 40–50% moisture removal; for low grade coals, typically, calorific value increasedfrom 20.45 MJ/kg to 25.59 MJ/kg, and moisture content down to 10% from 25%; coupled with proprietary briquetting solutions
Drycol® (DBAGlboal Australia)	under laboratory development	A pilot plant is to be constructed	High drying energy efficiency >97% due to selected excitation of water by microwave radiation; low temperature (<90°C) and precisely controlled drying without degrading the coking and thermal properties of coal; moisture reduction by more than half; additional benefits of partial removal of sulphur, potassium and phosphorus
Other evaporative processes			
Solar drying	Pilot-scale demonstration	A 2200 t/y pilot plant has been commissioned at Hazelwood in the Latrobe Valley, Australia, in 1986	Use direct sunlight and unsaturated air for drying with low energy requirement of 0.4 MJ/kg of water removed; requires large land area and the production is seasonally variable depending on the climatic conditions; suited to low rank coals deposits in arid areas with low labour costs; the lumpy product can be used as alternative to briquettes
Non-evaporative process			
Thermal dewatering processes			
Fleissner drying	The batch process versions commercially available; the continuous version not commercially proven	N/A	The earliest thermal dewatering process, initially developed in Austria in the 1920s; this involves batch autoclave treatment of coarse lumps of low rank coal in steam at 180–240°C to express moisture from coal as liquid water; a lump product suitable for transportation; the batch-process is commercially proven, and a continuous version has been developed, not yet commercialised; fine coal (–10 mm) cannot be used; relatively high capital cost and operational complexity

Evans-Siemen process	Pilot-scale demonstration	N/A	Similar to Fleissner drying, but using hot water or oil rather than steam to heat the coal in a semi-continuous flow reactor; lump or granular coal, or coal slurry can be used
HTD or HWD	Pilot-scale demonstration	A 7.5 t/d pilot plant at the University of North Dakota, USA; a 1 m^3/h pilot plant in Australia	A slurry version of the Evans-Siemen process; involve heat treatment of a coal slurry to 275–325°C under pressure; overall energy recovery 97%; product recovery 90%; partial removal of some inorganic results in a clean coal; difficulties in remediation of expelled product water
CHTD (Exergen)	Successful pilot-scale demonstration	A 4 t/h pilot-scale demonstration in North Tasmania, Australia; Detailed Feasibility Studies finished for both 50 t/h and 4000 t/h	Similar to HTD, but the autoclave pressure is generated by the hydrostatic pressure in a deep (1000 m) shaft; the process uses about 2% of the raw brown coal's energy content
SCW (Ignite Energy Resources Pty Ltd)	A successful small pilot-scale (4000 t/y) demonstration in Sydney	Collaborating with TRUenergy in the 20,000 t/y (as-mined coal) Cat-HTR module in the Latrobe Valley, Victoria, Australia	The core to SCW is the Catalytic Hydrothermal Reactor (Cat-HTR) in which lignite is depolymerised to to produce valuable oil and upgraded low-moisture coal products; the process provides a vast potential resources of syncrude for the oil industry, which has a number of advantages over a comparable alternative, the Canadian tar sands
Mechanical thermal expression			
MTE	Pilot-scale demonstration	A 15 t/h quasi-continuous pilot plant at Niederaussem, Germany; 15 t/h demonstration plant in Victoria, Australia	MTE employs compression force to press low rank coal hardly to express its moisture as a liquid; use of both mechanical pressure and heat (at 150–200°C) in order to reduce the pressing time down to manageable levels of a few minutes; considered to be less costly than HTD in Australia; remediation of the expressed water is a key step towards commercial implementation
Aquex MTE continuous process	Prototype demonstration	N/A	A continuous operation version of MTE; trials showed the reduction of moisture content from 65% to around 50%
DME extraction	Laboratory-scale study	N/A	Use dimethyl ether (DME) as a solvent to wash brown coal placed in a fixed-bed under modest pressure but at ambient temperatures; DME extracts the moisture out of coal and can be recovered when the pressure is reduced; laboratory tests showed efficient reduction of the moisture content from 54% to only 4%, and low energy consuption of 0.95 MJ/kg of water removed; less organic contamination of the product water due the ambience temperature used
Novel drying technologies			
Microbial hydrolysis (Terra Genesis)	N/A	N/A	A 'cold' process that extracts the water from brown coal without using heat; microbial gasification process is a digestion system where a series of bacteria are used to hydrolyse the coal

Currently, the most widely used drying processes are the flash mill drying for PCC boilers and the steam tube drying for coal briquetting facilities; both use hot flue gas from an adjacent coal-fired boiler to facilitate drying. Flash mill drying is effectively an integral part of the milling system of modern lignite-fired PCC power plants (Couch, 1989). In this section, conventional drying processes are not discussed, and their detailed introduction can be found elsewhere (Couch, 1990; Li, 2004; Nunes, 2009). The latest development of more advanced drying technologies will be discussed.

5.1 WTA

WTA is a fluidised-bed based evaporative drying technology; the abbreviation stands for Wirbelschicht-Trocknung mit interner Abwämenutzung (fluidised bed drying with internal heat recovery). Based on the Steam Fluidised Bed Drying (SFBD) concept originated in Monash University, Australia, WTA has been actively developed by RWE (Germany) through several commercial-scale demonstration projects and is now very close to commercialisation. Alstom, RWE's partner responsible for system integration, believes it will be able to offer WTA technology in new brown coal fuelled plants after about 2012, but it may be available as a retrofit option before that (Stamatelopoulos, 2007).

WTA has two variants: the closed cycle and the open cycle, as shown in Figure 9. The two variants differ in that the steam providing the heat comes from an external source or is the evaporated moisture from the raw coal. In both variants, the raw coal is fed into an atmospheric pressure fluidised bed dyer after being ground down to less than 2 mm in hammer mills. The fluidising medium is the steam arising from the drying process. The heat needed for drying of the coal is provided by hot steam via a heat exchanger immersed inside the dryer. In the open cycle, the hot steam is extracted from the low pressure part of a steam turbine in an adjacent power plant; for the closed cycle, the evaporated moisture from the coal, after cleaning, needs to be pressurised in a compressor up to 0.4–0.5 MPa and then used as the heating source. In the closed cycle, the sensible heat of the vapour condensate from the heat exchanger is used to pre-heat the raw lignite to approximately 65–70ºC.

It has been found that the grain size of coal fed into the dryer affects the drying efficiency significantly. Use of finer grain coal can increase the heat transfer efficiency by about 80%. Furthermore, the amount of steam needed for fluidisation in the dryer can also be reduced by about 70% compared to coarse grain coal. As a result, the size of the equipment and components required in the WTA system can be reduced significantly with finer coal feed.

The open cycle version was chosen for WTA pilot plants at Frechen as well as for the first WTA prototype system integrated into RWE's lignite-fired Niederaussem Unit K power plant. This fully assembled WTA system enables 25% of the firing capacity to be supplied by dried lignite, equivalent to around 210 t/h (or 110 t/h of dry lignite). The resulting net gain in the cycle efficiency is of the order of four percentage points, depending on the moisture content of the raw coal and the required final moisture content of dried coal. RWE is promoting the development of power plants fuelled with 100% dry lignite. However, this necessitates new boiler design, as discussed in Chapter 2.

The next technological milestone for WTA is the Hazelwood 2030 project, which provides an opportunity for the first commercial application of the WTA lignite drying technology. The existing Unit 1 of the Hazelwood power station, located in the Latrobe Valley in Victoria, Australia, will be upgraded to fire a mixture of dried brown coal and run-of-mine brown coal with increased output close to 220 MWe. An open cycle WTA system will be installed to provide the dried proportion of coal feedstock. To allow for burning a high proportion of dried brown coal, the boiler and the firing system need to be modified accordingly. Six new dried brown coal burners with a firing capacity of approximately 55 MW each will be arranged in the boiler walls. Following the modifications, the Hazelwood Unit 1 will be able to operate in the following three modes: mixed firing (50% dried brown coal:50% run-of-mine brown coal), 50% dried brown coal only and raw run-of-mine coal only.

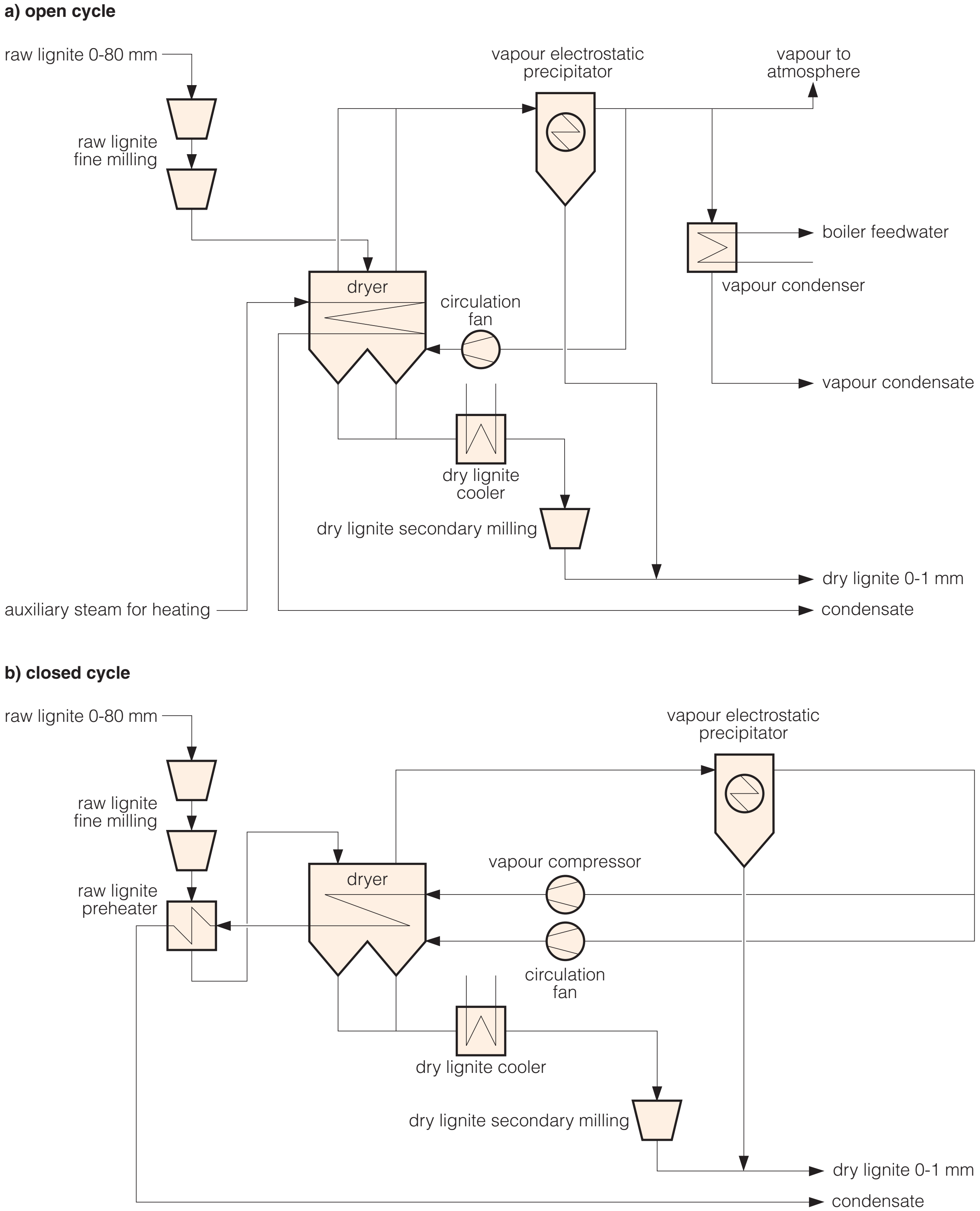

Figure 9 The schematic of the WTA drying process

The Hazelwood 2030 demonstration project will cut greenhouse gas emissions by about 21% of current value (Rich and others, 2007).

5.2 DryFining™

DryFining™ is a lignite fuel enhancement system that can not only dry but also beneficiate raw lignites, as shown in Figure 10. A unique feature of DryFining™ is to use the waste heat generated by a power plant as the heating source, which would otherwise be wasted. Known previously as Lignite

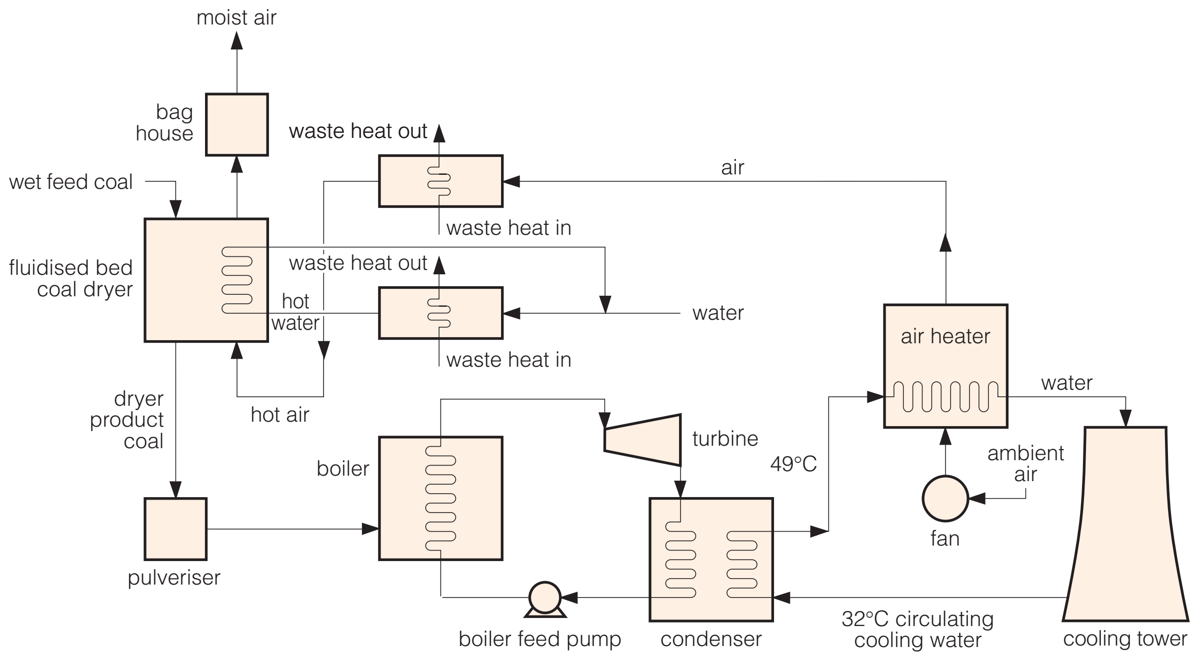

Figure 10 The schematic of DryFining™

Fuel Enhancement System, this technology was patented by Great River Energy under the new trademark in June 2010. In partnership with the US Department of Energy, Great River Energy installed a full-scale commercial system with four 135 t/h (raw coal) dryers at Unit 2 (600 MW) of its Coal Creek Station in Underwood, North Dakota, in 2006 (GRE, 2010). The system was commissioned in December 2009 and began to supply refined dry lignite coal, called DryFine™, to the Coal Creek Station. GRE also expanded beyond the scope of the US DOE project and self-funded another installation of four dryers on Unit 1 (600 MW) after recognising the economic benefits of this technology in previous prototype trials. At Coal Creek Station, the coal drying component of DryFining™ can reduce the moisture content of coal from about 38.5% to approximately 29%, which correspondingly increases the heating value of coal from 14.4 MJ/kg to 16.5 MJ/kg (GRE, 2010). As a result, the DryFining™ system reduces fuel input into the plant by about 14% by weight and increases the overall power plant efficiency by 2–4% (GRE, 2010). The refining component segregates the lignite stream and removes the denser fractions that contain high levels of sulphur and mercury. Stack emissions are therefore reduced: SO_2 reduction of 52%, overall NOx reduction of 32% and 40% reduction in mercury (GRE, 2010). DryFining™ therefore has potential for power plants burning high moisture coals. Taking the USA for instance, currently there are 35 power generation units burning lignite with a total capacity of 15 GW and 250 units (100 GW in total) burning Powder River Basin subbituminous coal with a high moisture content (GRE, 2010). Great River Energy has selected Worley Parsons Group as its engineer and commercialisation partner to license this technology worldwide.

5.3 Superheated steam drying

An effect of the aforementioned drying technologies is the partial oxidation of dried coal due to presence of air. In most cases, this effect is undesirable as oxidation may lead to potential risk of fire or explosion and coal degradation. Those concerns give rise to superheated steam drying in which air is absent so that oxidation of coal and fire/explosion risks can be effectively reduced. Superheated steam drying has long been used for drying biomass and agricultural products, but has been rarely applied to low rank coals. As coal applications are becoming more lucrative, many suppliers now started to test their processes on low rank coals. Superheated Steam (SHS) and Superheated Steam Dryer (SSD™) are two commercially-available processes of this type.

5.3.1 SHS

SHS is developed by Drying Solutions, an Iowa-based American company specialising in a range of drying technologies. As shown in Figure 11a, SHS uses superheated steam at temperatures between 135ºC and 538ºC whilst maintaining atmospheric pressure throughout a sealed airless environment, which is self-contained with small condensers and therefore does not require a boiler. SHS enables lower demand on odour control and lower greenhouse gases emissions. It reduces risk of fire or explosion and carryover of fine dust. All these result in improved energy efficiency and ease of environmental compliance. It also has the potential for energy recovery from steam.

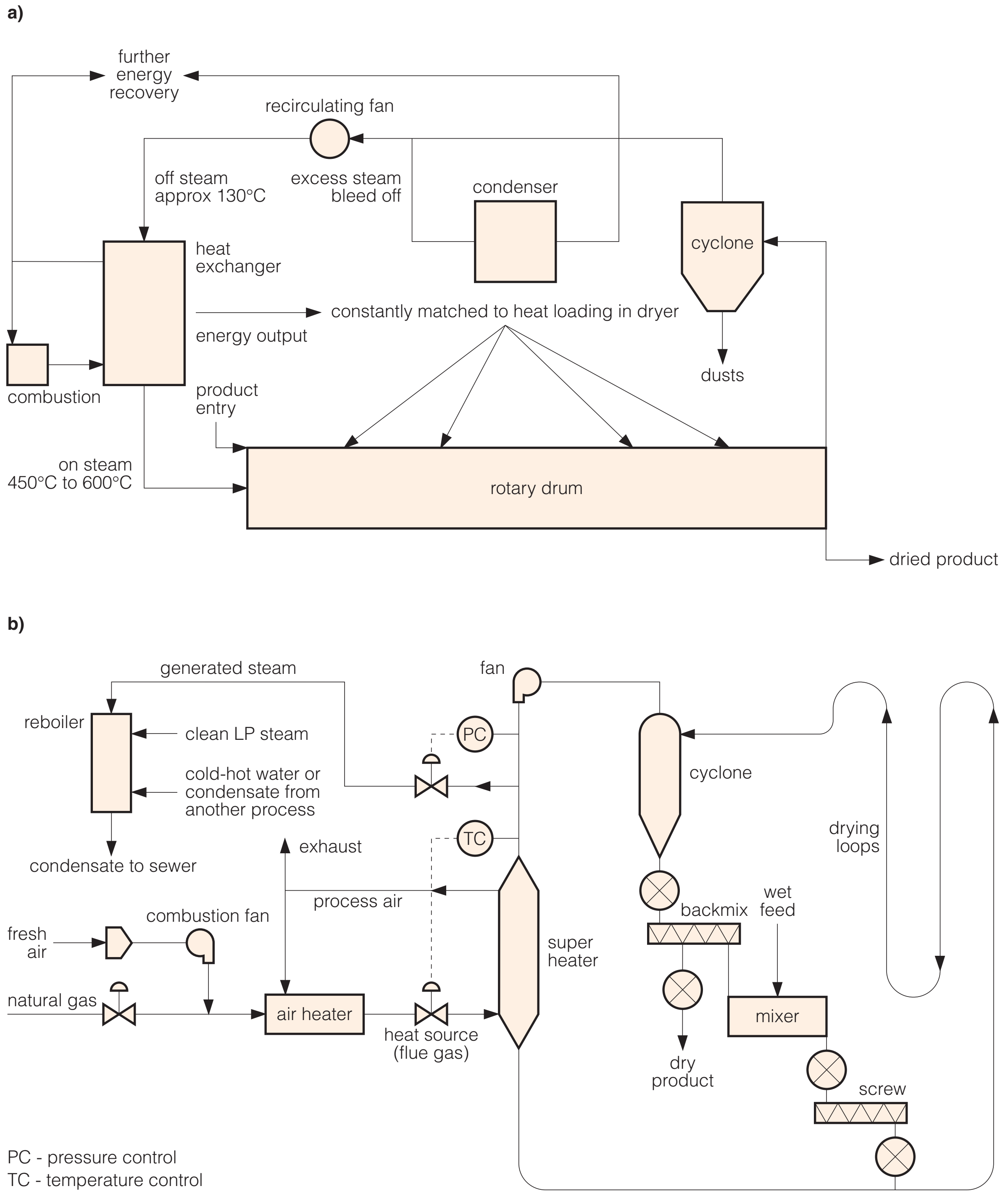

Figure 11 (a) The schematic of SHS; (b) the schematic of SSD^{TM} with backmix system and re-boiler for sticky sludge-like material

5.3.2 SSD™

The SSD™ technology is developed by The UK-based GEA Process Engineering. SSD™ is a closed loop pneumatic conveyor type dryer, as shown in Figure 11b. The wet solids are fed into the flow of pressurised superheated transport steam by means of a pressure-tight rotary valve, plug screw or similar. The transport steam is superheated indirectly in a tubular heat exchanger by medium pressure steam, flue gases or thermal oil. Alternatively, electrical heating may be used. Moisture is vaporised from the wet solid in the drying duct, forming transport steam and lowering its degree of superheat. The residence time in the system is normally 5–60 s. A second superheater can be used if necessary to achieve the required dryness. Transport steam and the dried product are separated in a high efficiency cyclone and the product is discharged from the dryer by means of another tight rotary valve. From the cyclone, the transport steam is recycled by a centrifugal fan to the inlet of the first heat exchanger; the excess steam generated, normally at a pressure up to 0.4 MPa, is continuously bled off. The excess steam can be reused either directly or to generate clean steam via a re-boiler. If there is no external use for the excess steam, it may be recompressed to 1–2 MPa and then used as a heating source in the superheater. This type of energy recovery is called Mechanical Vapour Recompression (MVR); power consumption is usually 150–200 kWh/t evaporated water (GEA, 2010). Primary energy consumption of SSD™ is about 750 kWh/t of evaporated water without any heat recovery. 70–90% of the energy is recoverable by reusing generated steam in another process for heating purposes, or by using MVR. The generated steam can produce about 200 kWh electricity per tonne of steam if a condensing turbine is used.

5.4 High velocity air flow drying

This type of drying technology makes use of high velocity and high pressure air to shatter coal particles so that moisture contained within the coal pore structures can be released. Since both the moisture content and particle size of coal decrease, drying and grinding can be achieved simultaneously, thus eliminating the difficulties attendant to grinding sticky low rank coals. There are three systems of this type under development.

5.4.1 DevourX mill

DevourX mill is a highly effective and efficient fine grinding system, which employs aeroacoustics rather than mechanical force to reduce the particle size of solid materials. Aeroacoustics is the science of acoustic noise generation caused by aerodynamic forces interacting with surfaces. DevourX brings a number of economic benefits. Its high efficiency leads to reduction in processing costs and energy consumption. It also eliminates many handling issues associated with use of mechanical force. Furthermore, DevourX requires a much smaller space for installation and less maintenance during operation, hence resulting in significant savings in capital expenditure and operational costs. Drying is achieved without the use of heat. However, the drying efficiency of DevourX can be enhanced by utilising the excess heat produced in a power plant, which is otherwise difficult to dispose of. Currently, there are two models of DevourX, referred to as M36 and M54 respectively. M36 can process from 25 t/h to 80 t/h, while M54 can process up to 200 t/h. DevourX Plc (Malaysia) is now licensing its technology through either user agreements or joint venture agreements across the world.

5.4.2 LamiFlo™

The second system is LamiFlo™ developed by LF Pumping (Europe) Ltd. This integrated electricity-driven process combines material handling/pumping, drying and air classification in one pass, and has been used for drying, transporting and grading more than 80 different materials

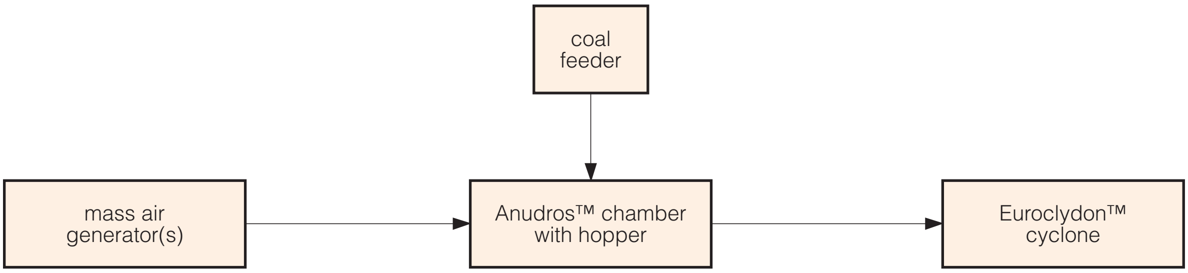

Figure 12 The schematic of LamiFlo™ (LF Pumping, 2010)

including oil shale, carbon pellets, graphite, coal ash, anthracite (up to 50 mm) and bituminous coals (up to 150 mm). With bespoke equipment design, capacities of up to 500 t/h (raw material) are now available. As shown in Figure 12, LamiFlo™ consists of three bespoke components connected with coated flanged pipe work: the mass air generator, the Anudros™ expansion chamber and the Euroclydon™ cyclone. A rotating Archimedes screw feeder feeds a moist feedstock into the Anudros™ expansion chamber in which 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). During the travelling, the air envelopes the moist solids and evaporates the surface moisture; high-speed impact of solid particles also results in reduction of particle size. The delivery pipe, typically 6 m long, can vary in length to suite the available space at a site. The mixture finally travels into a sealed Euroclydon cyclone, where the ground solids are separated from the saturated air stream and exit the system for storage or the next-stage application. The residence time of moist feedstock in the system is about 3 s and up to 10% surface moisture content can be removed per pass through the system. Since LamiFlo™ is capable of pumping coal up to 500 m and simultaneously reducing the moisture content when the material exits the system, it provides a two-purposes-in-one action solution for handling low rank coals. The estimated operating cost is 0.40 £/t and electricity usage 5.70 kW/t when a 40% moisture content lignite is reduced to a target moisture content of 22% at an output rate of 100 t/h (based on the cost of electricity 0.07 £/kWh). The carbon emissions are also low, only 0.94 kg/t (LF Pumping, 2010). The final dryness of the product is dependent on the feed particle size distribution.

5.4.3 Alligrator mill

Alligrator (Australia) Pty Ltd also provides a mill system that is in principle a high-speed, wind-swept impactor with only one moving part. Pulverisation is achieved by material to material impact with hammer speeds of 100 m/s and accelerated particle speeds of up to 200 m/s (Alligrator, 2010). This impact action occurs within an artificially induced vortex which, by nature of the shape of the mill, causes size reduction without the use of screens. This milling system requires an input material no larger than 25 mm and gives a dryer and finer grind in one pass. Product temperature is on average 4–8ºC above ambient; air conditioning and water cooling can be employed to facilitate further cooling if an even lower operating temperature is required.

5.5 Densification and drying

This type of technology was originally developed at Melbourne University, Australia, to convert Victorian brown coal into a material known as Densified Brown Coal (DBC). Its special feature is the attritioning where a kneader or sigma blender reduces the coal particle size to 5–10 µm so that the water is released from the coal matrix through physical disruption and collapse of the coal pore structure. The expelled water is mixed with coal to form a coal-water slurry that can be readily extruded into pellets or blocks of convenient dimensions. The extruded product is then air dried at ambient conditions, with or without the assistance of a draught, to form a dry densified product that possesses a net wet specific energy similar to that of bituminous coal. During the drying step, the pellets/blocks shrink, and strong inter- and intra-particle attraction forces, due to the presence of ionic association, develop to produce a hard and dense product. The crush strength of the dried products is found to be dependent on the pH values of the initial slurry. A downside of this process without the assistance of a draught is that the air drying process is too slow to produce significant output. Early studies, however, also found that accelerated drying of raw coal pellets, for example using hot gas and waste heat, would reduce the strength of the pellets (Allardice and others, 2004). This problem arises from the lag between fast drying and shrinking outer shell and the remaining wet core, which thus weakens the structure of the pellets and leads to breakage and degradation. Many attempts have been made to address this problem, and two processes have been relatively successful and have undergone extensive development.

5.5.1 Coldry™

The Australian company, Environmental Clean Technologies Ltd (ECT), is developing the Coldry™ process which uses low grade waste heat from an adjacent power plant to facilitate drying. The flowsheet of this process is shown in Figure 13. Coldry™ produces a feedstock in the form of densified pellets that are stable, easily storable and transportable and of similar calorific value to many black coals. It has been estimated that CO_2 emissions from an existing lignite-fired power plant can be reduced by 5–15% if 10–30% of the feedstock is replaced by Coldry™ pellets (ECT, 2010). It is possible to burn 100% Coldry™ product in significantly upgraded lignite-fired plants. There is also potential for diversifying the utilisation of Coldry™ product into other applications, for example, coal-to-liquids, urea and coke manufacturing. With the financial support from the Victorian Government's Sustainability Fund, a Coldry™ pilot plant has been established and operated in a batch-production mode from 2004 to 2007. During 2007, further development focused on the integration of its water recovery system and modifications to achieve continuous, steady-state production. The pilot plant has a maximum production capacity of around 10 kt/y, but is now only run for demonstration purposes. In July 2010, ECT signed a contract with a Vietnamese company, TinCom, to build a commercial Coldry™ plant in Victoria. TinCom will invest US$100 million. The plant will produce and export 2 Mt/y of dry brown coal to Vietnam from 2014 and will increase the production to 20 Mt/y by 2020 (VIIPIP, 2010).

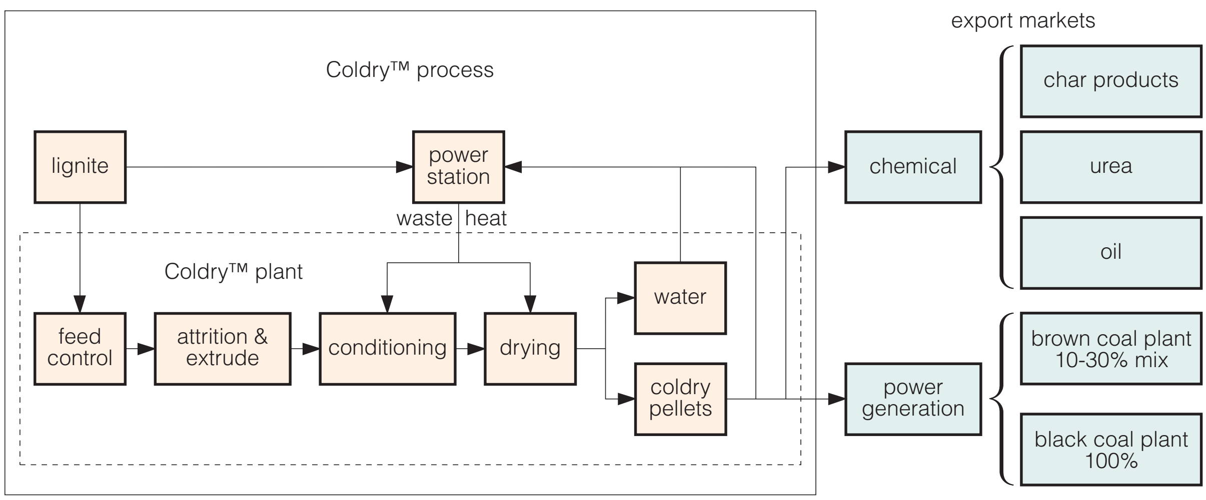

Figure 13 The flowsheet of the Coldry™ process (ECT, 2010)

5.5.2 LLD drying process

Another Australian company, the La Trobe Lignite Developments (LLD), is developing an integrated process that is based on densification/drying of brown coal. As shown in Figure 14, this process allows the selective combustion of only the hydrocarbons evolved from brown coal for the production of heat that is used for both electricity generation and drying of the remaining carbon in coal. Since the evolved hydrocarbons have low emissions equivalent to natural gas, this process enables clean power generation. It transforms the remaining carbon into high value metallurgical coke or activated carbon; a dry transportable brown coal product can also be produced although this is not the most economically or environmentally sound outcome (*see* Table 8). In addition, the process allows the

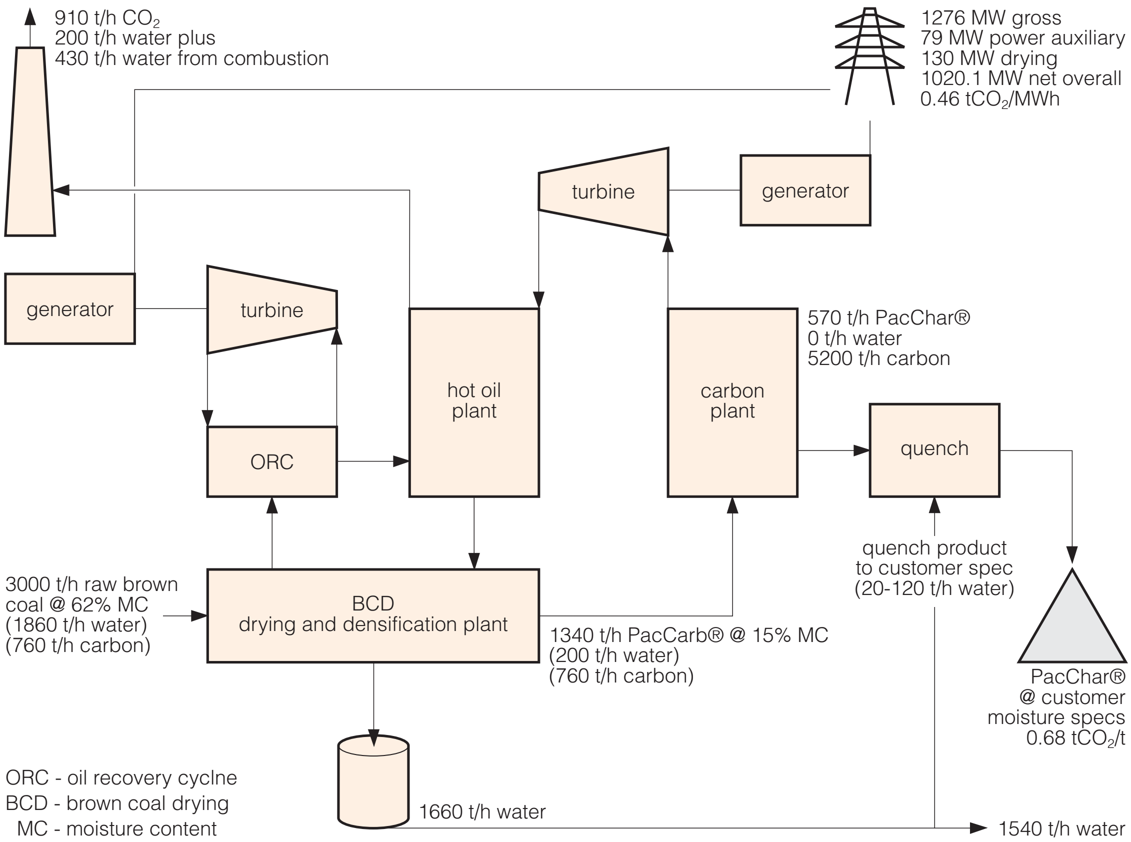

Figure 14 The flowsheet of the La Trobe Lignite Developments process (LLD, 2010)

Table 8 The solid carbon products from the La Trobe Lignite Developments process

Product	Features
PacCarb®	A dry transportable (non-pyrophoric) brown coal with most of the moisture removed; can be produced in either pellet or briquetted form; typically, fixed carbon 46–52%, volatile matter 45–55%, ash 2–4%
PacChar®	A dry carbon product with almost all of the volatile hydrocarbons removed; produced in briquetted form; typically, fixed carbon 90–92%, volatile matter 2–5%, ash 3–6%
PacCharCo®	A soft metallurgical coke equivalent, suitable for Electric Arc Furnace application, and with all of the moisture and hydrocarbons removed; available in waterproof briquetted form using binder; typically, fixed carbon 90–92%, volatile matter 5–10%, ash 4–7%
PacAtCharb®	An activated carbon suitable for water treatment application and a range of other processing uses; typically, fixed carbon 90%, ash 10% max. Note: the given typical results of proximate analysis are based on products produced from the high quality lignite found in the Latrobe Valley in Victoria, Australia. Specific properties will vary dependent upon the inherent properties of the lignite used as the raw material

recovery and re-use of all of the moisture contained in the raw coal. A batch-process pilot plant has been operated successfully in Victoria at a rate of 0.5 t/h; a detailed engineering design for a fully-integrated 25 t/h test & development plant has also been completed, but its construction will be subject to obtaining the necessary funding. The developer is also working on an engineering design for 10 t/h using its existing equipments. This drying process will be incorporated into LLD's planned 100 MW power plant in the La Trobe Valley in 2010 and a 1000 MW plant by 2015.

5.6 Microwave-based drying processes

This type of process exploits the fact that moisture responds to excitation of microwave energy much more intensively than coal mass. Consequently, water in coal, including both surface and inherent moisture, can be removed effectively by evaporisation whilst the coal mass remains at low temperatures. This desirable low temperature drying thus maintains the coal mass as intact as possible, preventing the processed product detracting from coal's original thermal and coking properties.

5.6.1 Drycol®

Drycol®, being developed by DBAGlobal Australia, is a continuous drying process using microwave radiation. Figure 15 shows the operating principle of Drycol®. 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. Tests have shown that Drycol® has a high efficiency for coal drying due to the selective adsorption of microwave energy by coal moisture; for washed metallurgical coals, the drying efficiency is in the range 62–94% (Graham, 2008). Drycol® has also been demonstrated to reduce the moisture content of a Powder River Basin coal by more than half (from 28% to 12%) at a rate of 25 t/h (Nunes, 2009). The moisture content of the output can be easily and precisely controlled through power setting and adjusting the conveyor speed. An additional benefit obtained from this process is the partial removal of a number of polluting elements contained in coal, including sulphur, potassium and phosphorous. Sulphur reduction is probably the result of reduction of pyrite into pyrrhotite, which is induced by microwave radiation. However, it has been found that sulphur reduction was dependent on coal type and that the greatest reduction had occurred on low power setting. There are also interests in using Drycol® for moisture control of either coking coal or vitrinite-concentrates (Graham, 2008). A Drycol® pilot plant is being considered in the USA.

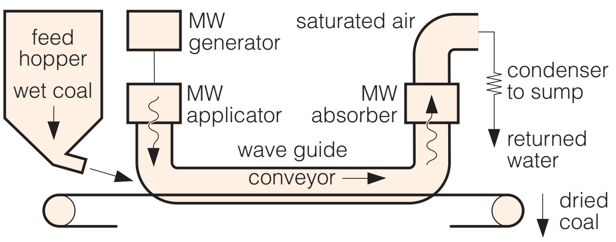

Figure 15 The schematic of a Drycol® machine (modified from Graham, 2008)

5.6.2 CoalTek Process

The Georgia-based CoalTek Inc has developed and commercialised a proprietary continuous microwave-based drying process. 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. It is deployed in a modular manner, thus making scale-up easy and cost effective. The CoalTek process has been proven at commercial scale at the company's 15 t/h facility in western Kentucky, which has been in operation since late 2007. Typically, 40–50% moisture removal is achievable. CoalTek Inc deploys its process in four market segments: power generation market, metallurgical coke/steel production market, coal conversion market and waste recovery market.

5.7 Hydrothermal dewatering processes

Non-evaporative dewatering processes involve the removal of moisture from the coal in liquid form, thus saving the latent heat of vaporisation and hence reducing greenhouse gas emissions from the entire coal drying process. Another benefit is that some of the 'dissolved' inorganics in the coal, sodium in particular, are removed in the liquid water, thus reducing the ash fouling propensity of the coal. Hydrothermal dewatering and mechanical thermal expression are two major types of non-evaporative coal dewatering.

Hydrothermal dewatering uses heat to, in effect, accelerate the coalification process and produces a harder product with reduced levels of moisture content, oxygen and porosity, and an increased carbon content and calorific value. This effect is attributed to thermal decomposition of the hydrophilic oxygen-containing functional groups in low rank coals, accompanied by the release of CO_2, shrinkage of the pore structure and their blockage with tars. Typical operating temperatures are in the 200–350ºC range, and the operating pressure is maintained above the saturated steam pressure to prevent evaporative drying of the coal. Since coal pores shrink and are sealed, water can not be reabsorbed to any appreciable extent. There is also less decrepitation than with evaporative drying because coal internal strain is less significant when the moisture is expelled in a liquid form. A disadvantage of thermal dewatering compared to evaporative drying is that a source of high pressure steam over 3 MPa is required. It is not appropriate to use 'waste', low cost, back-pressure steam from a power station unless additional heat is supplied. Therefore, the anticipated lower energy requirement for moisture removal may not be as great as it seems. Another major problem with thermal dewatering is the difficulty associated with effluent treatment. There is both organic and inogranic contamination of the expelled water. It is therefore costly to treat the water to meet permitted standards. This has been a major impediment to commercialisation of thermal dewatering processes.

A number of thermal dewatering processes have been developed since 1920. These include Fleissner process, Evans-Siemon process, UNDEMRC hot water process, Bechtel hydrothermal process, SPC process, IGT process, Koppelman process (noted for its high operating temperature up to 430ºC), WECO process, Hitachi process, Mitsubishi process, Kawasaki Industries' DK process and Russia's thermalcoal process. These processes have been introduced in detail in a previous IEA Coal Research report (Couch, 1990). Except for the batch Fleissner process, the other processes have not reached commercially-established status. This section will introduce three newer processes that have undergone considerable development towards commercialisation.

5.7.1 HTD

The Hydrothermal Dewatering (HTD), or less frequently referred to as Hot Water Drying (HWD),was developed at the Energy and Environmental Research Center of the University of North Dakota (UND-EERC). In the process (*see* Figure 16), a slurry of brown coal is heat-treated to around 300ºC in a reactor under sufficient pressure to prevent evaporation. Decomposition of the coal structure occurs under these conditions, which is analogous to accelerated coalification. This metamorphic change in coal expels the moisture in liquid form and liberalises light hydrocarbons, such as tars, from the coal. During the process, the coal pores shrink, collapse and are sealed by residual tars. As a result, the processed coal changes from hydrophilic to hydrophobic. After cooling and depressurising, a pumpable slurry product with energy content greater than the as-mined coal is obtained with excess water removed. This product can be fired in conventional boilers and has potential with more development for use in a coal slurry fired gas turbine combined cycle system (Allardice and Young, 2003).

The technical feasibility of HTD has been established at the UND-EERC's 7.5 t/d pilot plant in the early 1990s. Subsequently, the State Electrical Commission of Victoria in Australia (SECV) further demonstrated this technology at a 1 m^3/h pilot-plant scale. These studies confirmed that:

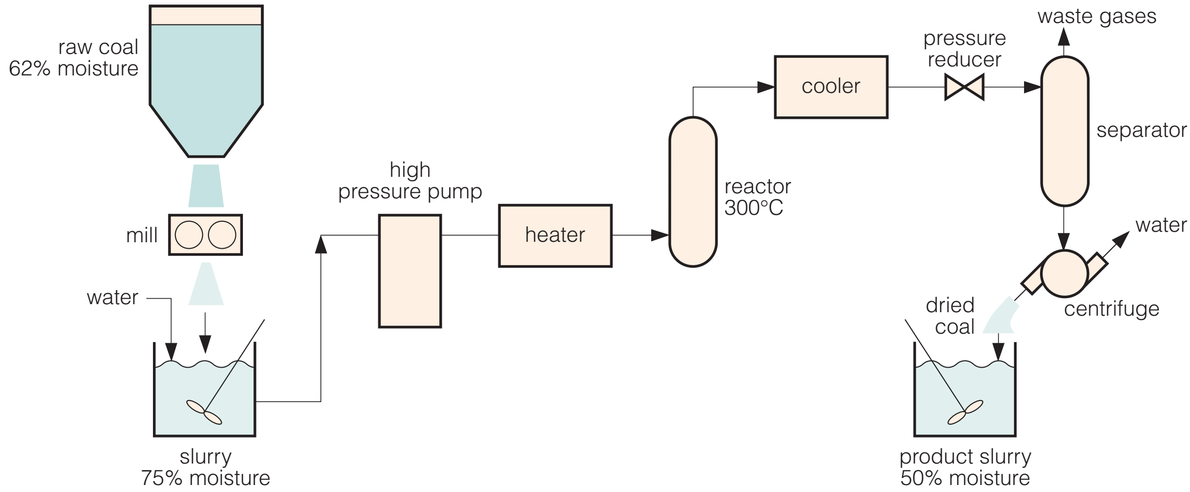

Figure 16 The schematic of the HTD process (Allardice and Young, 2003)

- treatment temperature at 275–325ºC was capable of non-evaporative moisture reduction;
- the overall energy recovery was about 97%;
- the average dry solid recovery was over 90% including losses due to soluble organic material and to water and gas released as a result of coal structure breakdown during the process. For Morwell and Loy Yang coals, the soluble organics removed within the water was about 1% (on dry coal basis) and the CO_2 yield of 5.0–6.5%;
- the process also removed some inorganic constituents from the coal. Acid washing or the addition of multivalent exchangeable cations to the feed slurry achieved further reduction of ion exchangeable elements such as sodium;
- several processes have been used for effluent treatment with limited success, highlighting the difficulties of effluent clean-up.

The Cooperative Research Centre for Clean Power From Lignites in Victoria has conducted further studies on the HTD process, but the process is no longer being pursued as an option for mine-side power generation in Victoria because of the high capital cost, particularly of the heat exchangers, and the costly wastewater treatment. There is a Japanese HTD variant, called Coal Water Mixture (CWM), which reportedly produced a slurry product with a higher solid density (Hiromoto and others, 1997). This improvement may be partly due to the use of surfactants. CWM has been tested on Indonesian brown coals, but the developers were discouraged by the high cost and difficulty of cleaning up the wastewater. A recent Japanese study demonstrated that the organic contaminant of the HTD effluent could be completely removed by pressurised hydrothermal gasification at temperatures as low as 350ºC using a novel Ni/carbon catalyst (Nakagawa and others, 2004). This new technique may increase the potential for HTD to convert brown coal into a clean, safe, exportable form.

5.7.2 CHTD

The Continuous Hydrothermal Dewatering (CHTD) process was developed by Australia's Exergen for continuous drying of brown coal. The core to CHTD is a vertical autoclave that uses gravitational head pressure and a small amount of energy to transform the molecular structure of brown coal to remove up to 80% of its moisture content. The flowsheet of this process is shown in Figure 17. The employment of the hydrostatic pressure eliminates the need for high pressure pumps, but the autoclave has to be as long as 1000 m. The process exerts about 10 MPa of pressure at 300ºC upon a brown coal slurry in the autoclave for a few minutes. These conditions decarboxylate the brown coal and cause the pores in coal to collapse and be sealed by evolved tars. Coal therefore changes from being hydrophilic to hydrophobic. The decarboxylation reaction is exothermic and contributes energy to the process; the overall process consumes only about 2% of energy contained in the wet brown coal. The

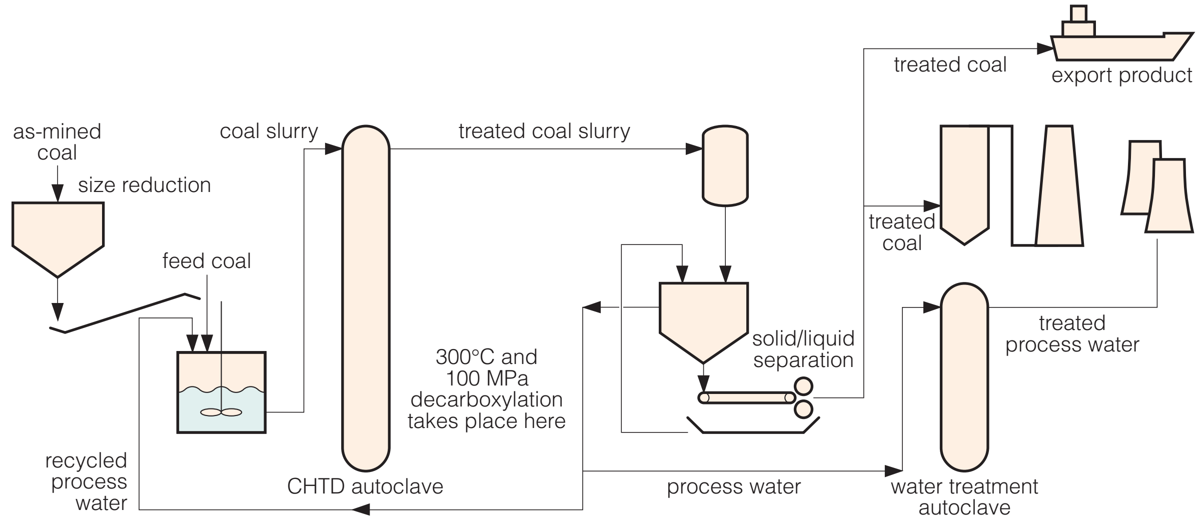

Figure 17 The flowsheet of Exergen's CHTD (Exergen, 2009)

processed coal can be exported or used in power stations. An additional benefit is that the expelled water can be used to replace 40% of the make-up requirement for the cooling water of an adjacent power station. Exergen's CHTD has been successfully demonstrated at a 4 t/h pilot plant in Beaconsfield, Northeast Tasmania. Coals from Victoria's Latrobe Valley and other Australian and international locations have been upgraded with almost uniform benefits. The moisture content can be reduced from 60–70% to 20–25%, and the LHV of coal can be increased to around 19.5 MJ/kg from 9 MJ/kg of the raw brown coal (Exergen, 2009). Exergen has recently completed a Detailed Feasibility Study for a proposed 50 t/h demonstration plant and a 4000 t/h commercial-scale facility. Exergen aims to work with its shareholders to develop a 12 Mt/y coal export project based on Victoria's extensive brown coal deposits.

5.7.3 SCW and Cat-HTR

Ignite Energy Resources (IER) Pty Ltd, a Melbourne-based Australian company, has developed a propriety Supercritical Water (SCW) reactor to convert low-valued biomass or coals into high-valued oil and coal products. The SCW-based system is shown in Figure 18. Its unique feature is the use of the continuous flow Catalytic Hydrothermal Reactor (Cat-HTR) technology to depolymerise lignite within minutes at high temperature and under pressure. SCW thus transforms lignite valued at 5–8 $/t into cleaner high-value products valued at around 100 $/t. IER owns rights to Exploration Licences in the onshore Gippsland Basin in Australia, which contains at least 18 Gt of lignite resource. With SCW, it is estimated that this vast lignite resource can be converted into approximately 18 billion barrels of oil and 5 Gt of cleaner coal products (IER, 2010). Hence the lignite sources provide a vast potential new source of syncrude for the oil industry. Lignite syncrude has a number of advantages over a comparable alternative, Canadian tar sands. Refinery of tar sands utilise a large amount of water (typically 2–4.5 barrels of water per barrel of syncrude produced), while the SCW-based syncrude production produces water at a rate of 0.6 barrels of water per barrel of syncrude produced, which is usable, though non-potable. The IER technology has about 50% lower carbon emissions than tar sands extraction because no steam or hydrogenation is required for the production of coal-derived syncrude (IER, 2010). Moreover, the capital expenditure of the tar sands extraction process is four times higher than the IER technology (IER, 2010). A 4000 t/y small pilot plant has been operating in Sydney for 24 months. IER has signed a hosting agreement with the major Victorian based utility, TRUenergy, to place its first 20 kt/y (as-mined coal) Cat-HTR module on an existing lignite mine adjacent to the Yallourn Power station in the Latrobe Valley. In this way, IER can save five years for the commercial demonstration development. The processed coal product will be used as fuel in the Power Station, which can reduce TRUenergy's CO_2 emissions by up to 60% (IER, 2010). IER also

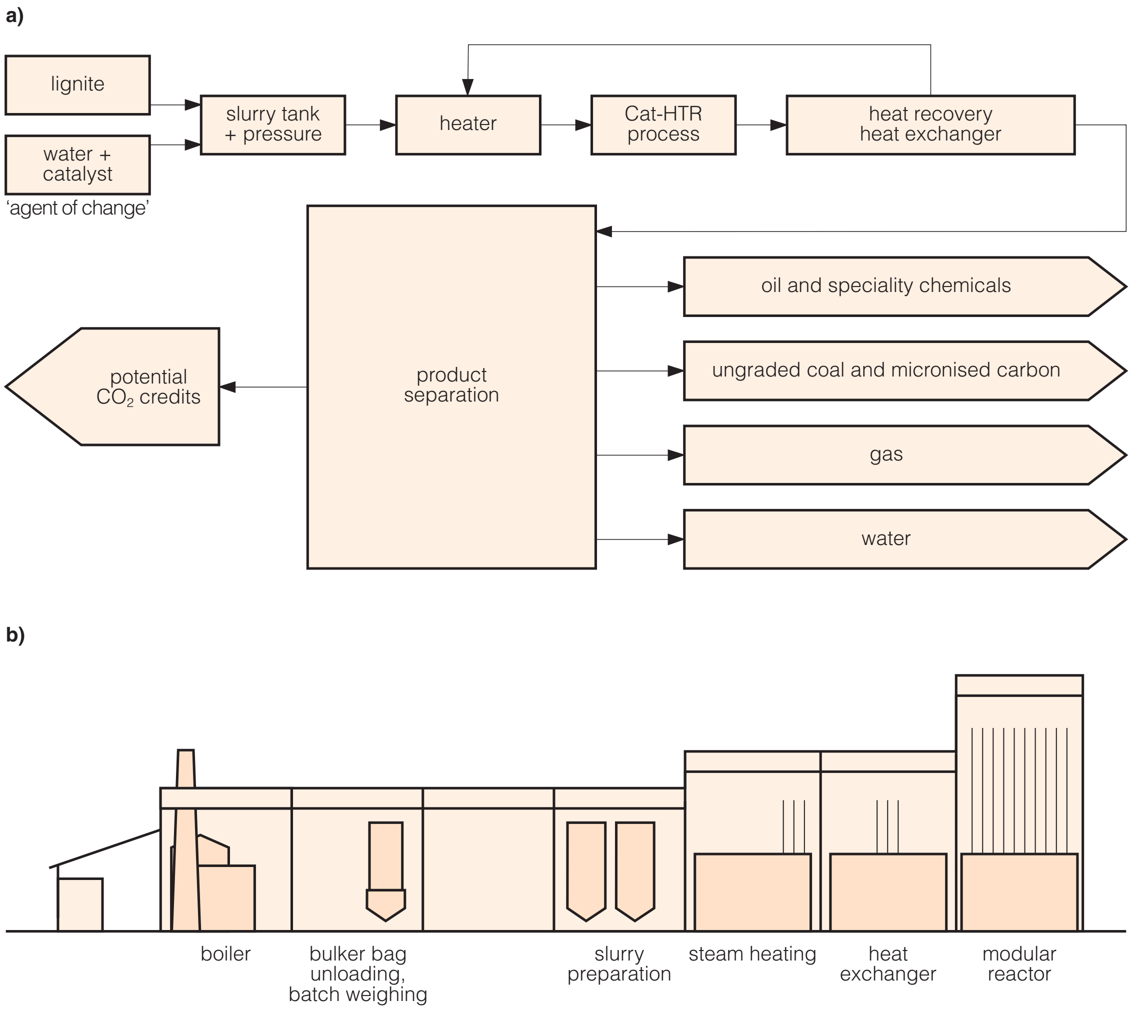

Figure 18 (a) the flowsheet of IER's SCW reactor (b) the layout of the designed SCW module (IER, 2010)

signed an agreement with Solid Energy to further develop and commercialise the technology in New Zealand. The two partners will construct and commission a pilot plant that is able to process lignite and biomass with a capacity up to 1 Mt/y . However, this project was cancelled by Solid Energy in late 2010 (Solid Energy, 2010).

5.8 Mechanical thermal expression

Initiated by the University of Dortmund, Germany, Mechanical Thermal Expression (MTE) employs compression force to compress low rank coal so that the moisture is squeezed out of the coal as liquid water. The dewatered coal is then subject to flash evaporation after the pressure is relieved. A typical MTE batch process is shown in Figure 19. Earlier studies are focused on MTE operating at ambient temperatures. However this was found to be impractical due to the high mechanical pressure and the

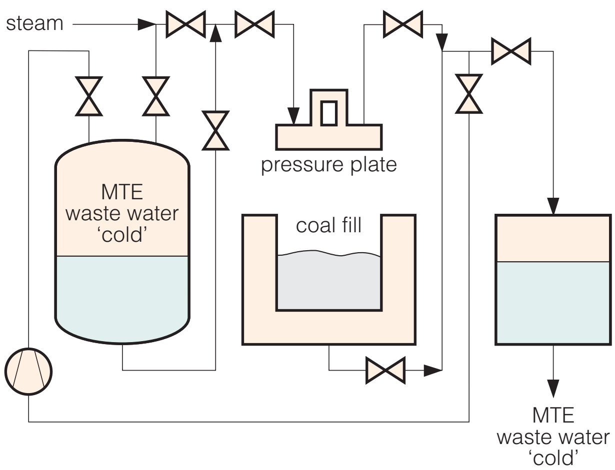

Figure 19 The schematic of a MTE batch process (Allardice and Young, 2003)

long pressing time (at least 20 minutes) required. Subsequent studies found that the combined use of heat and pressure could effectively reduce the pressing time to manageable levels (a few minutes). This is realised by heating the coal by steam to 150–200ºC prior to the application of pressure.

There has been active development of this process in both Germany and Australia. In Germany, an important development towards commercial implementation involved converting the batch process to quasi-continuous fully-automatic operation, with a throughput of approximately 1.6 t/h of dried coal (Katalambula and Gupta, 2009). In parallel with this, RWE investigated the pre-treatment of the raw brown coal, the feeding mechanism in the quasi-continuous process, and subsequent treatment of dewatered brown coal. RWE demonstrated this process at a scale of 15 t/h (dry coal) at the Niederaussem power station using a plant based on particle board press. This, however, was considered unsuccessful (Bergins, 2005).

In Australia, the Cooperative Research Centre (CRC) for Clean Power from Lignite has been developing a different configuration of the MTE process as a practical concept for retrofitting to existing boilers or for pre-drying of the feed coal for an IGCC plant. The CRC concluded that MTE is less expensive than HTD or WTA (Butler and others, 2007a). On this basis, White Australia has constructed a 15 t/h demonstration plant at Loy Yang Power site in the Latrobe Valley, Victoria, and intends to progress to a 200 t/h demonstration plant (Butler and others, 2007b). In addition, Aquex Pty Ltd in Australia has commissioned a prototype demonstration of a continuous mechanical expression process. A mesh steel conveyor belt was employed to facilitate the continuous loading, processing and discharging of coal. This continuous process reduced the moisture content of coal from about 65% to around 50% (Godfrey, 2010).

Similar to HTD processes, expressed water contamination with both organics and inorganics presents a major concern to the commercial implementation of MTE. Compared to the higher temperature used in HTD, the MTE process causes changes principally to the physical structure of coal due to the lower temperature used. It is interesting to compare the quality of water expelled from MTE and HTD. A direct comparison has been made by Butler and others (2007a) for brown coals from three major Latrobe Valley mines. It was found that MTE removed about 73–78% of the water, while HTD removed slightly less amounts of water (63–66%). The amount of dissolved organic carbon (DOC) in the product water increases significantly with temperature, as is evident from the fact that HTD water had a five times higher concentration of DOC than MTE water for each brown coal. The inorganic composition of the product waters resulting from MTE and HTD processing of the same coals were significantly different. Ag, As, Cd, Cr, Cu, Hg, Mo, Ni, Sn and Zn were found to be present in greater amounts in MTE-derived waters than in HTD-derived waters. However, HTD product waters were found to contain greater amounts of Al, B, Ba, Ca, Fe, K, Mg, Mn, Na, Pb, Se, Sr, Tl and V. A number of elements were found to be in concentrations exceeding permitted discharge standards. Although leaching of some elements, mainly Cu, from the experimental rigs might have contributed to their excessive concentrations, the results still indicated the potential problems with disposal or reuse of the product waters. Remediation of the product waters from both HTD and MTE is therefore necessary.

In addition to the pressurised catalytic hydrothermal gasification mentioned in Section 5.7.3, the use of raw brown coal as an adsorbent appears to be a promising remediation strategy (Butler and others, 2007b). Brown coal itself has the capacity to remove dissolved organic and inorganic components from aqueous solutions. The removal of inorganic species from aqueous solutions at low pH values is associated with the ion exchange capacity of brown coal. The carboxyl groups (and to a lesser extent the phenolic groups) present throughout brown coal are responsible for the ion change properties. Under appropriate conditions of pH, these groups can exchange protons and facilitate the formation of metal carboxylate salts (Lafferty and Hobday, 1990). The removal of organics from aqueous solutions is due to their adsorption onto the coal matrix. Butler and others (2007b) found that there were strong linear relationships between the concentration of DOC in MTE product water and the absolute amounts adsorbed onto individual coals. Moreover, as the pH of the MTE water/adsorbent solution increases, the amount of DOC remaining in solution increases. This might be associated with the known tendency of humic acids to solubilise at higher pH values. In the study by Butler and others (2007b), the removal of DOC ranged from 41% to 71%, while the removal of inorganics was modest. There was substantial removal of divalent and trivalent cations. However, the coals had less affinity to adsorb Na and K, which were also abundant in coals themselves. Approximately 5–6% of the feed coal to the MTE drying process would be required to remediate the product water to levels described in the study (Butler and others, 2007b). There are two possible options for using the spent adsorbent coal. It can be fired with fresh coal feedstock in a power station boiler, so that the recovered organic and inorganic components from the MTE product water go ultimately into fly ash, flue gas and fouling deposits on boiler heat exchange surfaces. Alternatively, it can be incinerated, possibly for metal recovery or for final disposal. There were also attempts to use a microbiological fixed bed process for MTE product water treatment in Germany. This approach was adapted from a process to treat wastewater from coke manufacture. However, only limited details are available from work by Reich-Welber and Felgener (1993).

6 Upgrading of low quality coals

Although drying is an important upgrading method, there are some other technologies dedicated to transforming low quality/rank coal into high value, stable and transportable fuels. These technologies generally incorporate drying as a component, and are discussed as follows.

6.1 Briquetting/pelletising

Briquetting/pelletising is a long-used method of coal upgrading and provides fuel in varying size for domestic use, for small boilers and moving bed gasifiers, and for industrial application purposes. The raw material is usually low cost, either coal fines or typically low rank coal. Limestone can be added to capture sulphur in combustion. Briquetting/pelletising results in a fuel with more consistent properties and increased ease of handling. Some pollutants and moisture present in feedstock coal can be partly removed during the briquetting/pelletising process. Consequently, the product is cleaner and emits less CO_2 than the feedstock. Briquette production requires a low moisture content, while pelletising is more tolerant of moisture content (up to about 30%). A number of technologies are available including mixer agglomeration, disk pelletisers, roller presses and extrusion (Couch, 2002). The choice of technology is dependent on four key factors: the nature of feedstock, the requirement for the product (such as strength, moisture content and calorific value), the price spread between the raw feedstock and the product, and the cost and availability of binders. A binder is used for non-caking coal fines or some run-of-mine coals, while for some coals with certain properties no binders are needed. The roller press and extrusion are widely used for briquetting. Hot briquetting, where the coal is preheated to approximately 400°C and becomes softened, can reduce the difficulty of making briquettes. Disk pelletisation and roller pelletisation are two common pelletising technologies. A rotatory tubular dryer is commonly used to facilitate drying for these coals.

Coal briquetting is currently undertaken in a number of countries. In the USA, CoalTek and Southern Coal Handling have been operating a 120 kt/y plant in Calvert City, Kentucky, and will expand its output capacity. CoalTek also have plans to build additional coal upgrading facilities to meet the growing demand. In Germany, RWE operates three upgrading plants: Fortuna-Nord (1.7 Mt/y), Frechen (1.8 Mt/y) and Ville/Berrenrath (0.7 Mt/y) (RWE, 2010). Lignite briquettes have been used as a domestic fuel for many decades. And the producers are now seeking new markets such as wastewater treatment or as a soil improver. RWE developed a product called Ireland briquettes with a sulphur content suitable for the Irish market and the regulations applicable there. This product consists of 70% lignite and 30% hard coal and there is a production capacity of 10 kt/y at the Frechen briquetting factory.

Australia has two major players in coal briquetting. Energy Brix Australia Corporation, a company of the HRL group, produces briquettes from Latrobe Valley brown coal using a binderless technology. The technology is the same as that used in Germany. The product is dried to 15% moisture and contains relatively low levels of ash, sulphur and nitrogen. Current production capacity is 1 Mt/y, with opportunities for expansion of both domestic and export markets. White Energy developed the Binderless Coal Briquetting (BCB) process which applies heat to raw coal for drying followed by roller briquetting. BCB has been used to briquette both bituminous coal and subbituminous coal. The moisture content can be reduced to 2–5% for bituminous coals and to 7–10% for subbituminous coals. White Energy has a demonstration plant at Cessnock in New South Wales, Australia, which can be used to test and analyse different coal samples as well as train its staff. It partners with Bayan Resources to form a joint venture that owns and operates the coal upgrading plant in Tabang, Indonesia, and is responsible for the marketing and sale of the upgraded coal, known as KSC Supacoal. The joint venture already runs a 1 Mt/y upgrading plant, and plans to expand its total capacity to 15 Mt/y (White Energy, 2010). Typically, the subbituminous coal from the Tabang mine can be upgraded, with its calorific value increasing from 18.7 MJ/kg to 25.6 MJ/kg (White Energy, 2010). In the USA, White Energy has entered into agreement with Buckskin Mining Company to develop a coal upgrading plant at Buckskin's mine in Gillette, Wyoming. The plant will have an initial capacity of 1 Mt/y, and the parties intend to expand the capacity to 8 Mt/y. A tentative site has been selected for construction of the first upgrading module. White Energy and Peabody Energy Inc also entered into an agreement to pursue the development of coal upgrading at Peabody's Caballo Grande Mine in the Powder River Basin near Gillette, Wyoming. The project will be constructed in phases with an initial capacity of 1 Mt/y and then expanded to 20 Mt/y over a five-year period. White Energy has also pursued opportunities in South Africa with Black River and China with Black River and Datang International Power.

In China, it is the issue of large quantities of coal fines that arouses interest in briquetting. There are hundreds of coal briquetting plants, most of which have small production capacities. The market for briquettes has been relatively small, because coal has been readily available in production regions. However, this situation might be changing with China's coal demand surging significantly in recent years. There are also inadequate technical standards; low quality binders such as clay are widely used, thus resulting in a poor quality product that can crack easily during transport or storage.

6.2 Advanced coal upgrading technologies

This section discusses some advanced coal upgrading technologies that have been developed in recent years. These technologies have reached either pilot scale or commercial demonstration scale with projects undertaken in Indonesia, the USA and China.

6.2.1 K-Fuel®

The Evergreen Energy Inc, a Colorado-based US environmental solution company, offers its commercially validated K-Fuel® technology. As shown in Figure 20, K-Fuel® is a low rank coal refining process that applies high temperature (204–260ºC) and pressure (2.7–3.4 MPa) to crushed raw coal in the K-Fuel® processor. Under such harsh conditions, the physical and chemical structure

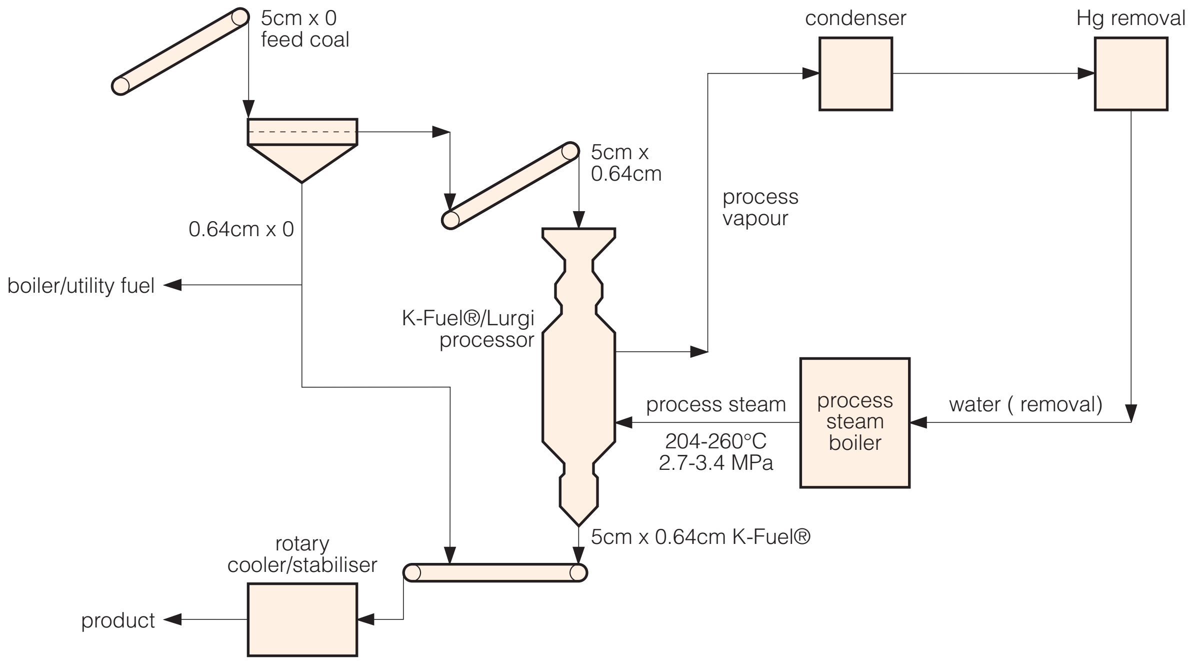

Figure 20 The flowsheet of the K-Fuel® process (Evergreen, 2010a)

of the low rank coal is altered so that a clean, low-moisture, higher heating value fuel is produced. The K-Fuel® process is a development of the strategic alliance between Evergreen Energy Inc and Sasol-Lurgi since 2003.

Successful test burns of K-Fuel® refined coals have been made in eight power generation facilities in the USA. The results confirmed the improved combustion efficiency and reduced air emissions (CO_2, NOx and SOx) as a co-benefit. A number of lignites and subbituminous coals were used in those tests, and results are shown in Table 9. The moisture content can be reduced by more than half, and the heating value is increased by 18–55%. Significant mercury removal is an additional benefit that is highly desirable. In a month-long test burn of coal blend in 2007, Evergreen Energy Inc found an almost 82% drop in mercury emissions at the stack of a western Pennsylvania power plant, compared to local coal only operation at the plant. The blend comprised 75% Ohio bituminous coal and 25% K-Fuel® refined coal from Wyoming. This could reduce by two-thirds the amount of costly activated carbon the power plant would have to inject in order to comply with Pennsylvania's strict mercury emission standard (Business Wire, 2008). The results suggest that blending local coals with the K-Fuel® refined coal offers utilities and industrial users a near-term, effective and cost-saving solution to meet new stricter mercury emissions standards taking effect in the USA since 2010. The added fuel flexibility would not only result in cost savings but also bode well for the continuous mining and use of local available coal resources. The K-Fuel® incorporated blending may be more important for industrial boilers because many of them are too small to install scrubbers or injection on a cost- effective basis.

Table 9 The quality improvement achieved by the K-Fuel (modified from Evergreen, 2010b)

Coal origin	Raw coal, MJ/kg	K-Fuel®, MJ/kg	Moisture removal, %	Mercury removal, %
Wyoming, USA	19.7	24.1	53.1	73.4
Louisiana, USA	15.5	20.7	67.3	76.1
Inner Mongolia, China	15.9	20.2	60.3	44.7
India	18.2	21.5	69.8	53.4
Indonesia	15.2	23.6	83.4	78.5

A pioneering 750 kt/y K-Fuel® production facility was built near Gillette, Wyoming, USA, and began production at the end of 2005 (Katalambula and Gupta, 2009). Production and process development work at this plant, representing a more than US$100 million investment, was made possible by Bechtel Power Corporation. This work led to an enhanced design of K-Fuel® refinery process that offers significant process, economic and environmental improvements. K-Fuel® has so far been patented in 33 countries, and Evergreen Energy Inc is now working with Bechtel Power Corporation to commercially deploy this technology globally. In 2010, Evergreen Energy Inc reached an agreement with Beijing Gang Jing Hong Ren Technology Co Ltd to establish a joint venture called Evergreen China Energy Technology Co Ltd. The joint venture has 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 currently under development (Evergreen, 2010c). In addition, there are known opportunities in Indonesia.

6.2.2 Upgraded Brown Coal (UBC®)

UBC® is an adaptation of the slurry dewatering technique used in the Brown Coal Liquefaction (BCL®) process developed in Japan and Australia. As shown in Figure 21, it consists of three stages: slurry preparation/dewatering, solid-liquid separation and briquetting. During the slurry preparation stage, the pulverised moist low rank coal is mixed with circulating oil (normally light petroleum oil) and then laced with heavy oil (for example asphalt). The slurry is then fed into a shell and tube type

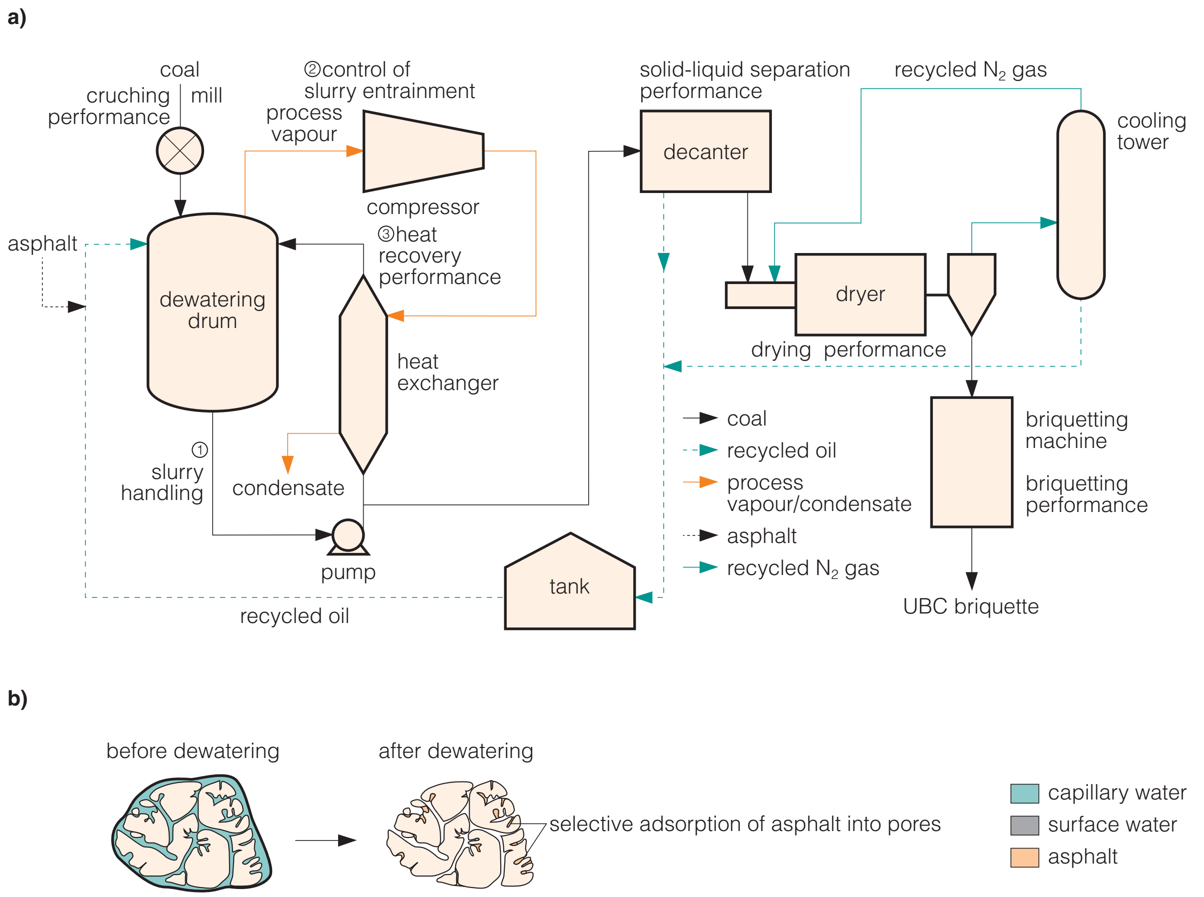

Figure 21 (a) The schematic of UBC® process (b) Change in the pore structure between raw and processed coal (Kinoshita and others, 2010)

evaporator where moisture in coal is removed as vapour at 150–160ºC and under pressure of 0.2–0.3 MPa. The water vapour is separated from the oil-coal slurry in a cyclone. To extract the energy of the vapour, it is pressurised in a compressor and then sent to the shell side of the evaporator as a heating source. This reuse of the evaporated vapour provides substantial energy savings during the dewatering stage. The oil solvent is recovered in a decanter and a tubular steam dryer (to recover the oil stuck in coal pores) connected in tandem. The upgraded product is in the powder form; for long distance transportation, it can be easily briquetted without the use of a binder. Since the heavy oil can penetrate into the numerous pores of coal particles during dewatering, the inherent moisture is therefore removed. Some heavy oil is inevitably absorbed onto the surface of pores, thus suppressing spontaneous combustion. The water-repellant nature of the absorbed heavy oil also prevents the dried coal from reabsorbing moisture. Since the moisture content is significantly reduced, the heating value of the upgraded coal, though it varies depending on the characteristics of the coal, is improved to around 25–27 MJ/kg (Sugita, 2003). It has also been confirmed that briquetted upgraded coal is similar to normal bituminous coal in terms of ease-of-handling and re-crushing. Moreover, upgraded coal has excellent combustion characteristics so that it can burn out easily and completely even under low NOx combustion conditions.

UBC® has reached the status of large-scale demonstration. In 2001-05, the Japan Coal Energy Centre (JCOAL) and the Indonesian R&D Agency of Energy and Mineral Resources had collaborated to build and to operate a 5 t/d (feedstock) process-demonstration plant in Cirebon, Java Barat province, Indonesia. The success of this pilot plant has prompted Japan's Kobe Steel to build a 600 t/d (product) demonstration plant on Kalimantan Island in Indonesia. It is located at Satui coal mine owned by the Kobe Steel's partner PT Arutmin Indonesia, which is abundant in low rank coal. The purpose of operating this plant is not only to demonstrate the feasibility of the process at large scale but also to produce a suitable amount of upgraded coal for evaluation as fuel in a commercial coal-fired thermal power plant. The plant was commissioned in early 2010. Kobe Steel expects to operate a commercial UBC® plant, which will have a capacity of 5000 t/d (product), after 2010. In Indonesia, more than half of mineable coal (4–7 Gt) is of low rank. Indonesian low rank coal is noted for its low sulphur and low ash contents. It can therefore be an attractive fuel provided it can be upgraded with an economical dewatering method. Indonesia is actively pursuing commercialisation of UBC® with the hope of unlocking the huge potential of its vast low rank coal reserve for energy export.

6.2.3 Syncoal®

Syncoal® is a stable, low ash, low sulphur product from Western SynCoal LLC's patented advanced coal conversion process (ACCP), as shown in Figure 22. The ACCP comprises thermal processing in two vibratory fluidised bed reactors coupled with physical cleaning in deep-bed stratifiers. A commercial demonstration of ACCP has been operating at a coal mine in Montana from 1993 to 2001. This operation produced and sold nearly 2 Mt of Syncoal® with a heating value of about 27.9 MJ/kg and S as low as 1%. After the sale of Western SynCoal LLC in 2001, SynCoal Partners LLC was formed to develop the next generation of ACCP technology known as SynCoal Gen2 System. Its major difference from the initial ACCP (also called SynCoal Gen1) is that it is designed for processing coal at the point of utilisation, thus overcoming the handling issues associated with transport of Syncoal® to remote power stations. The SynCoal Gen2 System significantly reduces both capital and operating costs compared to the Gen1 process. This is accomplished by selecting a simple and more energy efficient processor, simplifying the coal and gas flow pathing, modifying the product cooling operation and selecting a more efficient cleaning system. The SynCoal2 process can be integrated into existing power plant delivery systems allowing the plant operator to replace a portion of the present feedstock with Syncoal® without having to make expensive modifications to the boiler or furnace (SynCoal Partners, 2010). In this way, low cost lignite and subbituminous coal can be blended with Syncoal® to provide a suitable feedstock for power generation plants.

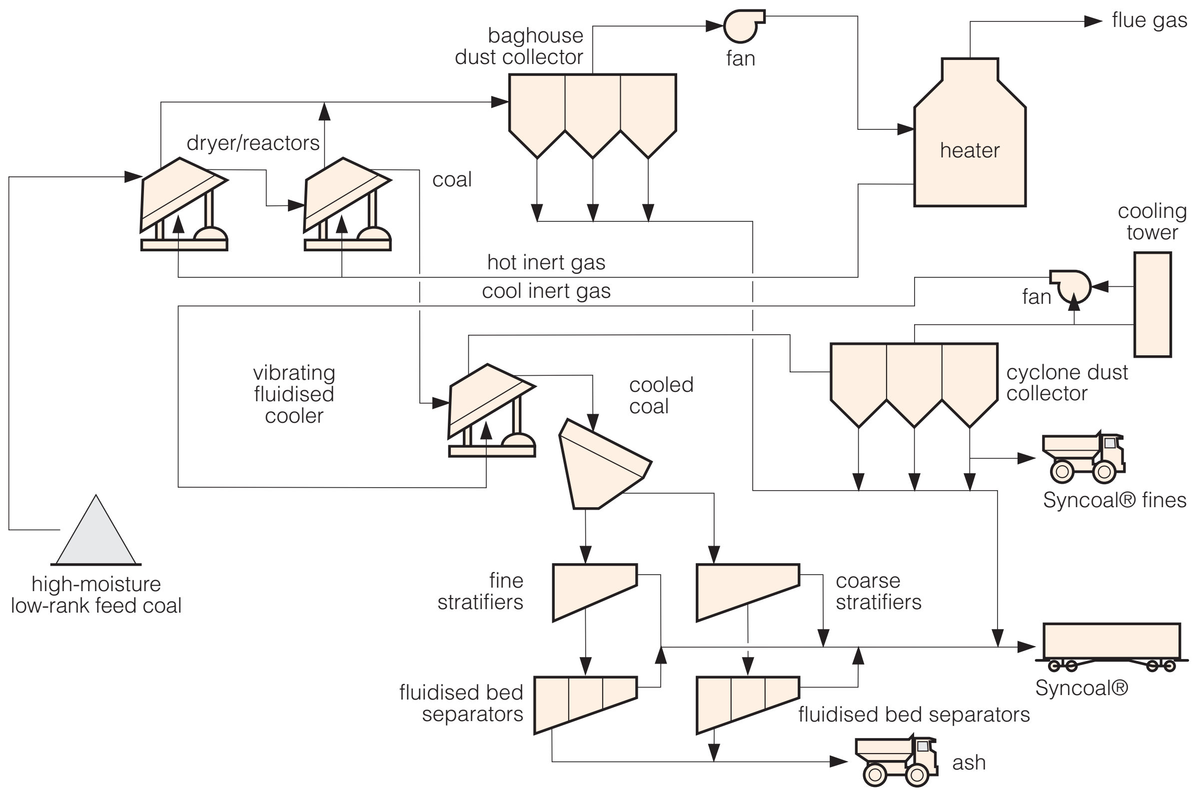

Figure 22 The schematic diagram of the ACCP process (NETL, 2001)

6.2.4 Cowboy Coal Process

The FMI New Coal Inc developed the Cowboy Coal Process for upgrading subbituminous coal from the Powder River Basin. The process involves a fluidised bed reactor in which partial oxidation of coal takes place and an oil/water cooler. It burns a portion of the feedstock, some 6–8%, to provide the heat for drying. Since established technologies are used for its components, the Cowboy process can be easily scaled-up in size. In addition to water removal, the process reduces the mercury content of the coal. The heating value of the product increases to 27 MJ/kg from 19 MJ/kg of the raw subbituminous coal (FMI, 2010). This patented process has been tested intensively at Batelle Laboratories in Ohio and Western Research Institute in Laramie, Wyoming. FMI operates a 20 kt/y large-scale demonstration plant to establish production capability, product handling and product stability.

6.2.5 CCI process

ConvertCoal Inc (CCI) has developed a proprietary technology for conversion of low rank coal to synthetic crude oil and solid clean-coal fuel. The synthetic crude oil is refinery ready and matches a mid-range crude oil quality. Its yield is 16–18% of the feed coal (on a water- and ash-free basis) or 0.7–0.8 barrels of oil per tonne of coal, depending on the feed coal composition. The yield of high quality clean coal fuel is 65–70% of feed coal, which gives 60–80% lower SO_2 and mercury emissions and has more than 40% higher heating value than the original low rank coal (ConvertCoal, 2010). This leads to 4–7% higher boiler efficiency and approximately 4–7% of CO_2 reduction per unit of electricity output.

The CCI coal conversion process is not in commercial operation at present. However, essentially all the process components and the corresponding equipment have been tested at the demonstration plant level or actually are in commercial operation in facilities with similar duty and capacity to established processing plants. For example, the SCI-Shell-DoE Encoal pyrolysis demonstration plant was operated successfully under very similar operating conditions on low rank coal at 500–1000 t/d coal from 1992 to 1998 in Wyoming. CCI has finished a reference plant design based on the concept of serving a 500 MW capacity of PCC or IGCC power generation station with clean coal fuel and producing approximately 8000 bbl/d of synthetic crude oil. This design uses commercially-available and tested equipment exclusively in order to reduce process uncertainty and commercial risks. It can therefore be argued that the major project financial risks are the pricing of coal and oil rather than in the area of technology performance (ConvertCoal, 2010).

6.2.6 GTL Energy process

GTL Energy, in Adelaide, Australia, developed a continuous upgrading process that combines mechanical expression, low temperature drying and briquetting to produce stable coal briquettes from low rank coals. The process uses high mechanical pressure prior to drying to express the water from the pores in coal. This allows for more efficient drying at low temperatures. Low temperature drying has a number advantages including lower operational cost, reduced emission profile resulting from less heat generation and few volatiles being released with moisture from the coal, ease with material handling and stability of end product. Another advantage of the process is that coal feed of any size can be accepted, thus ensuring full utilisation of the mined coal. The water removed can be recovered and has been shown to be suitable to make up the overall water needs of energy conversion plants. A demonstration plant is in operation in North Dakota, USA, which provides demonstration of concept at scale and a facility for coal testing and further technology development (Williams, 2011).

7 Coal cleaning

Similarly to low rank coals, the vast majority of low quality high rank coals is used in local power stations close to the mine, which have been designed specifically to accommodate the characteristics of the particular coal. With escalating demands on coal quality to increase boiler efficiency and reduce acid gas emissions, cleaning of low quality coal is essential for a power plant to meet specifications. Removal of the extraneous inert and mineral matter from coal prior to combustion can have multiple benefits. Reduction of the aluminosilicate clay minerals, which typically comprise 60–90% of the total coal mineral matter, will lead to a corresponding decrease in boiler erosion and fouling, and will decrease the amounts of fly ash and bottom ash generated. Removing pyritic minerals will decrease the sulphur emissions and lower or even eliminate the desulphurisation requirements for the flue gas.

Coal cleaning is normally applied to steam and metallurgical coals for export, where the increased product calorific value, reduced freight rates, and reduced problematic ash behaviour justify the cost of cleaning. Geographically, coal cleaning is more widely practised in OECD countries and major coal exporting countries such as Australia and Indonesia. There are two main types of coal cleaning methods: dry cleaning and wet cleaning. However, there is currently little incentive exists to clean low rank coals because these coals are mostly produced from surface mines and therefore have fewer extraneous mineral impurities than high rank coals from underground mines. In fact, a significant fraction of the inorganic constituents are incorporated and finely dispersed into the organic structure of low rank coals. Consequently, many conventional coal cleaning processes provide little or no benefit when applied to low rank coals. Furthermore, since cleaning adds to the cost of the final coal product, cleaning of low rank coals is widely regarded as not commercially sensible, taking into account the low price of these coals. In contrast, cleaning of high ash coals of high rank may bring desirable benefits, helping to alleviate the ever worsening operational problems in existing power plants or to expand the utilisation of these coals.

Given the relatively low prices and specific properties of low quality coals, there are limited types of technology suitable for their cleaning. Most importantly, the cleaning cost must be kept as low as possible, in addition to evaluation of the pros and cons of a specific cleaning technology. This chapter describes a number of cleaning technologies that are suitable for cleaning of low quality coals.

7.1 Wet cleaning of coals

Wet cleaning of coal is based on the difference in specific gravity in either water or a dense medium. A dense medium is a suspension of water and a heavy mineral, most commonly magnetite (particle size <44 μm), that gives the medium an adjustable specific density. A dense medium is used to improve the cleaning efficiency; its specific gravity typically ranges between 1.3 and 1.8. The magnetite can be recovered from clean coal and refuse using drain and rinse screens in combination with magnetic separators. Dense medium plants have higher capital and operating costs than the simpler water-only plants. However, their improved efficiency and ability to produce cleaner products often outweigh the higher costs.

Conventionally, a number of water-based processes is used in combination in a coal washery. To determine which process or what dense medium to use, and to predict the possible separation for a given coal, a washability analysis is necessarily made. Typically, the coarse coal is cleaned in a jig, which pulsates water through a bed of coal. This movement of the bed allows the raw coal to stratify with the heavy refuse moving to the bottom of the bed and being discarded. The lighter coal-rich fraction remains on the top of the bed and is recovered. For certain coals, the use of a dense medium is necessary; a dense-medium vessel is normally used for coarse coal to facilitate the dense medium separation.

The intermediate-size coal (top size 0.6–6.35 mm) is cleaned in a two-stage water-only hydrocyclone circuit. Mixed with water, the coal is pumped under pressure into the hydrocyclone where the lighter coal-rich fraction is concentrated towards the centre of the hydrocyclone and exits through the vortex finder, while the heavy refuse is forced towards the wall of the hydrocyclone and exits through the apex. Alternatively, a spiral concentrator can be used to clean this intermediate fraction effectively. Spirals can be configured in stages similar to that of the two-stage water-only hydrocyclone circuit or can be connected with a water-only hydrocyclone to form a two-stage circuit. For some coals, a dense medium is used in the hydrocyclone for their cleaning.

Generally, the fine coal is cleaned by surface-based techniques. These techniques, known as froth flotation or oil agglomeration, mainly exploit the difference in hydrophobicity or oleophobicity between coal and minerals. Hard coals are naturally hydrophobic, while minerals are mostly hydrophilic. Furthermore, coal is also oleophilic, while minerals are mostly oleophobic. When either oily collectors or frothers are added into a coal-water mixture, coals will preferentially attach to air-filled froth bubbles or oil droplets, while minerals will, for the most part, reject air or oil. The exceptions are primarily the oil-adsorbing clay minerals and the slightly hydrophobic pyrite.

This section will not describe the abovementioned conventional wet cleaning techniques in detail. Interested readers can refer to the references Bethell and Luttrell, 2005; Nunes, 2009 for detailed introduction. Various studies have confirmed that conventional coal washing techniques are not normally applicable to low quality coals due to their high moisture contents, different pore structures and surface properties compared to bituminous coals. These differences imply that the conventional washability analysis presents problems because, for instance, the ASTM flow-sink standard method (ASTM D4371-06) for determining washability characteristics was developed for hard (bituminous) coals. Although 'this test method in general has useful application in determining the washability characteristics of low rank coals, in the strictest sense, it is not necessarily the most technically correct test method' for low quality coals. This situation is broadly true for methods used in other countries. Special caution needs to be taken when the standard determination methods are applied to low quality coal (Couch, 1990). This is because there may be moisture loss through drying during sample preparation, oxidation and degradation of the coal during the determination, adherence of fines to coarser particles during size distribution analysis, and erroneous ash content measurement due to SO_3 retention in coal ashes with high calcite concentrations. New or modified methods for assessing the cleaning potential for low quality coals are therefore necessary. There has been some work on lignite in this regard by EPRI in the USA (Couch, 1990). Nevertheless, methods that are directly applicable to low quality coals have yet to be developed.

The inapplicability of conventional wet cleaning techniques is more marked with low rank coals. The close specific gravities of the coal substance and the mineral inerts in most lignites generally rule out the use of jigs. In such a case, dense medium separation is the preferable technique for cleaning lignites, although recovery of the dense medium material may be a severe problem if large amounts of fines are generated during cleaning. Hydroclones may be useful for pyrite removal or rejection of heavy free impurities in a pre-cleaning operation. Froth flotation is generally not successful with lignites due to poor selectivity; further development of appropriate additives is needed. Oil agglomeration is usually considered to be unsuitable for low rank, high-oxygen coals. It is necessary to use heavier oils than those used to treat bituminous coals. Nevertheless, oil agglomeration tests made in Japan suggested some benefits, that is a reduced tendency for both moisture reabsorption and spontaneous combustion of the cleaned coal (Yoshida and others, 1983).

***Case study*:** There is a different perspective on the cleaning of lignites in Turkey, because there are substantial domestic and industrial markets for lignites, in addition to power generation, in this country. Considerable quantities of Turkish lignite have a high ash content; for example, Elbistan and Seyitomer lignites have ash content in the range of 10–20%, while lignites from Tuncbilek can reach as high as 40–50% (Couch, 1988). At Tuncbilek, there is a 700 t/h lignite washery where 56% of the feed is processed by a Wemco dense-medium drum, 21% by dense-media hydroclones and 23% by fine coal jigs (Couch, 1990). There has been active research in cleaning of lignites in recent years. For example, Ceylan and Küçük (2004) studied the feasibility of cleaning three Turkish lignites by dense-medium separation and froth flotation techniques. Solutions of zinc chloride with specific gravities ranging from 1.1. to 1.75 have been used as the dense medium. In the case of froth flotation, methyl isobutyl carbinol (MIBC), diethyl isohexanol (DEH) and sodium dodesyl sulphonate (SDS) were used as the frother, and kerosene was used as the collector. The results indicated that the effectiveness of the cleaning techniques in ash and sulphur removal was considerably different for the different lignites. An effective pyritic sulphur removal (>90%) was obtained for Beypazan or Göba lignites by the dense-medium separation. The effectiveness of the froth flotation was relatively different depending on both the lignites and the frother type. The recovery was generally low and varied considerably depending on the frother type and the particle size.

Another important wet cleaning technique for low rank coal is ion exchange. This technique significantly removes alkali/alkaline elements from coal by exchanging other cations in an aqueous acid solution. Although the alkali/alkaline species normally account for less than 1 wt% of the raw coal, they play very important roles in the pyrolysis, gasification, combustion and liquefaction of low rank coals. For example, the volatilisation of these species, particularly sodium, may lead to severe fouling on the boiler steam reheat tubings, or cause severe problems for the operation of syngas-fired gas turbines due the corrosion/erosion of the turbine blades. Some of these species may act as good catalysts for the gasification/combustion of the char if they are retained in the char after pyrolysis.

Ion exchange has been investigated in both batch and continuous processes with hydrogen, calcium, magnesium, aluminium and ferric ions as the exchanging cations (Couch, 1990). The ease of replacement of ions from lignite follows the sequence as $Na^+ > K^+ > Mg^{2+} > Ca^{2+} > Al^{3+} > Fe^{3+} > H^+$; sodium is the least stable ion attached to the carboxylic or phenolic functional groups in lignite, while the hydrogen ion, as an undissociated weak humic acid, is the most stable. Laboratory tests have shown that sodium is most effectively removed by hydrogen ions from sulphuric acid solutions. Sodium removal was found to be a function of the size and moisture content of the coal, the ionic strength of the exchange ion, contact time, coal to acid solution ratio, and the equilibria between ions in the coal and solution. Exchanging alkali ions with calcium and/or magnesium brings the benefits of increased ash fusion temperature and sulphur retention capability of the coal. However, wastewater clean-up would become complicated when calcium and/or magnesium ions are used. Ion exchange brings about significant irreversible changes to the coal macromolecular structure because the carboxylic or phenolic groups are rearranged to suit the steric requirement of the exchanging cations (Hayashi and Li, 2004). This structural change has been verified by many experimental results. In a pyrolysis experimental study on ion-exchanged Victorian brown coal with Na^+, Ca^{2+}, H^+, the H^+-exchanged samples were found to give varied tar and total volatile yields when pyrolysed in a wire mesh reactor (Sathe and others, 1999). This was probably due to the mobilisation and loss of humic acids from the brown coal. The dried Na^+-exchanged coal became a cake rather than individual particles, while the ion-exchanged Ca^{2+} effectively cross-links two carboxylate or phenolic groups by bonding to them, resulting in a tighter macrostructure. Ion-exchanged cations may not be just bonded to the carboxylate groups, they could also be co-ordinated with other oxygen containing species, such as carbonyl and OH^-. Therefore, there is a possibility that additional oxygen is brought into the coal along with the ion-exchanged cations.

7.2 Dry cleaning of coals

For many decades, only small amounts of coal were cleaned with dry methods. The reason was the poor separation efficiency of dry processing and a properly earned negative reputation. However, there has been renewed interest in dry coal cleaning from the coal industry in recent years. The most important reason is the avoidance of water, which eliminates the need for fine dewatering and wastewater treatment. Dry coal cleaning also does not introduce the moisture penalty, associated with wet processing, to the cleaned coal product. In arid areas, dry coal cleaning may be the only economic and feasible technical option for fully-exploiting a high ash coal reserve.

Dry processing cleans coal according to differences in physical properties between coal and refuse, such as density, size, shape, lustrousness, magnetic conductivity, electric conductivity, radioactivity, frictional coefficient. Processes include the air jig, the aerodynamic classifier, the electrodynamic separator, the magnetic separator, the air-dense medium fluidised bed and the FGX separator. Brief descriptions for each of these technologies are given as follows.

7.2.1 Air jig

An air jig is a vibrating vessel in which coal particles are stratified due to alternate expansion and compaction by vertical pulsating air flow. Heavy refuse particles gradually trickle down to the bottom and exit the vessel, while light clean coal is concentrated in the top and recovered. An air jig is usually used for high specific-gravity separations. Until recently, the principal disadvantage of air jigging was poor separation efficiency, generally deemed as lower than that of wet processing. Over the past decade, there has been a fundamental advance in dry jigging efficiency. As a result, several new air jigging machines have bee introduced to the coal market; a good example is the Allair® with an automatic refuse removal control system, developed by the German company Allmineral GmbH & Co. Modern air jigging machines are environmentally friendly, due to both the elimination of water circuits and introduction of fabric dust collectors.

Historically, the coal industry preferred air jigs to other dry separating devices for removal of pyrites, clays and rocks from crushed run-of-mine coal and for recovering coal from the mine discards. The major reason is the considerably lower capital and operational cost of an air jig. Many surface coal mines lose 10% or more of their reserves due to mining methods that discard top and bottom layers and ribs. Air jigs can be used to recover a significant portion of this lost coal. Not only will this ‘opportunity’ coal provide a new revenue stream, it will also reduce the amount of waste handled and extend the reserve life of a surface mine. A project was undertaken in the USA to identify the benefits of improving the quality of lignite for power generation. As part of this project by EPRI, the University of Kentucky, and a number of other mining and power companies, hundreds of air jig separation tests were conducted on many different lignite seams (Weinstein and Snoby, 2007). The test results showed that modern air jigs can substantially reduce the ash content of the coal, resulting in increased heating values. Furthermore, a significant reduction in sulphur and mercury can be realised while achieving high energy recovery. The refuse generated by the process is a stable dry material that can be backfilled for rehabilitation of the mine.

Weinstein and Snoby (2007) also reported another example in Europe where 12 modern air jigs were retrofitted into an existing 600 t/h lignite cleaning plant. This original cleaning plant had 36 air tables and 48 wet shaking tables, along with a thickener, slime pond and auxiliary equipments for fines dewatering. Performance of the renovated plant with modern air jigs is identical with the original one, except for lower costs and halved labour requirement. The new plant was capable of improving the heating value of the lignite from 14.2 MJ/kg to 14.7 MJ/kg and reducing the sulphur from 5.8% to 5.5%.

Air jigs have also been used for improving the quality and consistency of Indian coals for their users. Indian coals are well known for being highly inter-grown with mineral matter (ash). It is not unusual for raw Indian coal to have an ash content in excess of 40%. However, due to regulations and other reasons, for example poor rail transportation conditions, few coal consumers in India have control over the source and consistency of the coal they received. OCL India Ltd has found modern air jigs useful to reduce the ash content from 40–45% to 34–37% (Weinstein and Snoby, 2007). This improved quality of coal significantly improved the operation and economics of OCL’s sponge iron plant. Meanwhile, a reject product with an ash content less than 50% was produced; this carbon-rich reject, blended with fines from the dust collector, could be acceptable to burn in a steam plant.

7.2.2 Aerodynamic separator

An aerodynamic separator operates on the principle that coal and refuse can be separated in an air flow due to their different densities. The heavy reject particles take a shorter trajectory, while the light coal particles take a longer one. The coal particles and refuse are therefore separated and collected in separate hoppers. The feed coal has to be closely sized to achieve a high separation efficiency. In practice a number of classifiers need to operate in parallel on the different sizes of a coal. Therefore, an aerodynamic separator generally has several air cells to receive the sized coals simultaneously. Each cell generates a laminar air flow with velocity commensurate with the particular size range. To ensure a high separation efficiency, each feed stream needs to be homogeneous and evenly distributed. The problem envisaged with an aerodynamic separator would be screening the raw coal into a number of sizes and handling these sized feeds and products. Dust control, collection, and disposal may also present some difficulties.

7.2.3 Electrostatic separation

Electrostatic separation uses the difference in the conductivity or dielectric properties between coal and associated mineral matter to separate these two under dynamic conditions. Figure 23 shows the schematic of a typical ‘high-intensity’ electrodynamic corona drum separator. A corona, generated by an electrode, is passed on to a rotating, grounded, metal drum, thus creating an electric field. When a fine coal is fed onto the rotating drum, a dispersed layer of the coal is formed and ionised. Because the mineral matter is relatively conducting, it becomes of equipotential with the charged drum and is therefore released. In contrast, the dielectric coal particles remain attached to the rotating drum and are subsequently scraped off the drum into the product bin. All particles are also subjected to centrifugal and gravitational forces. The splitters are used to divide the stream of released material for the most effective concentrations of reject, middlings and product. The separation efficiency has been found to be dependent on the voltage on the electrode, particle size, rotating speed of the drum and the properties of the feed. Generally, fine particles separate more efficiently with higher rotation speeds and lower voltages, while larger particles give better separation at lower rotation speeds and high voltages. For these reasons, the size of the feed is best kept within narrow ranges for a single pass unit. Multipass with provisions of sizing the reject and/or middlings would give a higher concentration of product than multipass separation alone.

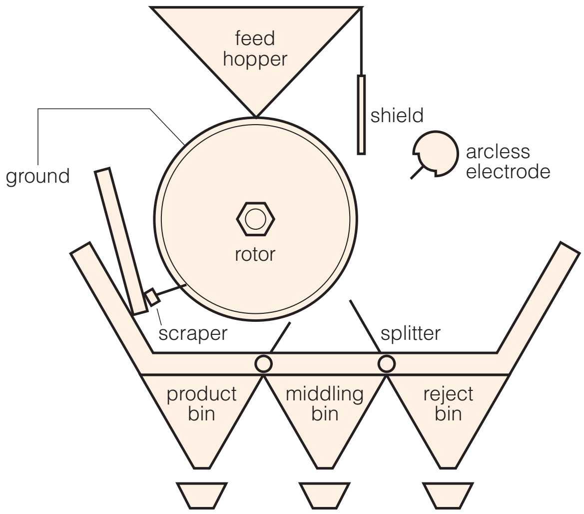

Figure 23 The schematic of a typical ‘high-intensity’ electrodynamic corona drum separator

Another electrostatic type of separation technique is the tribo-electrostatic (or called frictional-charging) separation. Tribo-electrostatics is a electrification process through particle-particle and particle-wall collisions, which is dependent upon the surface properties of the particles. Coal and mineral matter are charged with opposing polarity on contact or friction with a material having electro-affinity capability between the two. When the charged coal and mineral particles pass through an electric field, they are deflected towards electrodes with the opposite polarity, and are thus separated. The tribo-electrostatic separation is most suitable for fine materials. The separation efficiency depends on coal bulk and surface composition as well as particle size distribution

(Mazumder and others, 1995). Surface oxidation of coal has been found to be a hindrance to tribo-electrostatic separation (Soong and others, 2001). The reason may be that the oxygen species on the surface of coal reduce the tendency for carbon to lose electrons.

One proposed application of tribo-electrostatic separation is at a PCC power plant to remove the pyrite and ash-forming minerals from coal that has been ground in a pulveriser (Stencel and others, 1999). It is known that coal pulverisation, in conjunction with the pneumatic transport of coal particles within burner pipes, imparts electric charges to the particles (Nieh and Nguyen, 1987). Stencel and others (1999) investigated whether it was possible to utilise these charges to facilitate pre-burner beneficiation of the pulverised coal at two US utility power plants. The particle charges were measured by a designed sample probe immersed into the coal pipe between the pulveriser and burners. The absolute value of the average charge per unit mass was the same order of magnitude for both utility systems and was in agreement with values obtained within a laboratory system. Another probe device was used for in situ tests to determine whether these charges were sufficient to achieve tribo-electrostatic separation of combustibles and mineral matter. The test results gave positive indications; the field test results were also found to be in close agreement with those from laboratory tests on coals sampled from the same utility plants. This work indicated the potential for on-site pulverised coal beneficiation; a test facility was reported to be established to assess such a separation process further under conditions similar to those expected in burner pipes.

Electrostatic separation has been found to be particularly efficient in removal of pyrite from coal; the removal efficiency is high for high-vitrinite coals. The US DOE's National Energy Technology Laboratory developed a tribo-electrostatic separation process. In bench-scale tests on eastern US coals, it has been proven to be capable of >90% pyritic sulphur removal and >70% ash reduction. A continuous process has also been developed through a proof-of-concept scale demonstration (200–250 kg/h) built and commissioned at the University of Virginia Tech in the USA. The results showed that the best separation efficiency was obtained by combining pneumatic and rotary chargers in series. However, this two-stage configuration produced too low a recovery (49%) and reject ash (43%) to be commercially viable (Yoon and others, 2001). In the same study a economic evaluation was also made to assess the future commercialisation of this process. It was concluded that the tribo-electrostatic separation cleaning of power plant pulverised coal and intermediate mill products would not be economically attractive. Application to pulverised mill rejects, however, would offer reasonable returns. Nevertheless, the economic margins may improve as additional market premiums became available for lower ash and sulphur coal products.

7.2.4 Magnetic separation

Magnetic separation is based on the fact that most of the sulphur-bearing and ash-forming minerals in coal are paramagnetic and can be separated from the remaining diamagnetic carbon. This technique has recently been used in the MagMill machine developed by EXPORTech Inc. MagMill is a combination of a pulveriser with a continously operating open-gradient dry magnetic separator. Raw coal is ground in a pulveriser, and some hard mineral components such as pyrites are liberated. These gradually separated, based on particle size and density, from the soft coal and concentrate on the surface of the grinding table. A stream of these concentrated minerals is withdrawn from the lower regions of the mill and is passed to a dry magnetic separator located outside the pulveriser. The magnetic separator recovers trapped coal for return to the pulveriser and rejects the mineral refuses that otherwise would have gone to the burner. Over 70 coals from all major American coal basins have been tested for their response to magnetic separation (MagMill, 2010).

7.2.5 Air-dense-medium fluidised bed

An air-dense-medium fluidised bed (ADMFB) is a dry coal beneficiation process. By means of gas-solid suspension as the beneficiation medium, light coal and heavy minerals can be separated from each other in a fluidised bed according to the difference in their densities. The gas-solid fluidised bed with a uniform and stable density can be formed using magnetite powder or a mixture of the power and fine coal. Using tight control of the fluidisation and bed composition, a separation density range of 1300–2200 kg/m^3 is achievable (Chen and Wei, 2007). The capital and operational costs of an ADMFB are lower than those of wet cleaning processes of the same capacity, due to elimination of the complicated coal slurry circuits. Compared to air tables and jigs, this technology requires smaller volumes of air with lower pressure and generates less severe dust emissions.

The Mining Processing Research Centre of the China University of Mining and Technology (CUMT) has been developing an ADMFB machine since 1984 (Chen and Wei, 2007). A schematic diagram of this machine is shown in Figure 24. Separation of the heavy minerals and light coal is achieved by a moving chain conveyor that scrapes off the two fractions from the fluidising zone towards opposite directions. An efficient dry separation condition requires stable dispersion fluidisation and microbubbles to ensure low viscosity and high fluidity. To minimise the uneven velocity distribution and displacement of the bed, both air flow and medium particle size distribution must be well controlled. A number of advantages have been reported of the ADMFB machine (Katalambula and Gupta, 2009). It can achieve precise separation, favourably comparable to the best existing wet dense-medium beneficiation for 6–50 mm sized coal with a probability error E_p of 0.05–0.07. E_p represents the degree of inaccuracy in the split between the floats and sinks at the separation density. Its capital and operating costs are only half of those for similar-scale wet beneficiation processes. This machine has a wide range of beneficiating densities, typically 1300–2200 kg/m^3. As a result, this technology can meet the needs of beneficiating different coals for multiple products. It can be used either to remove gangues at high density or to produce clean coal at low density. This technology also has a low environmental impact because of its low-noise operation and dust removal system.

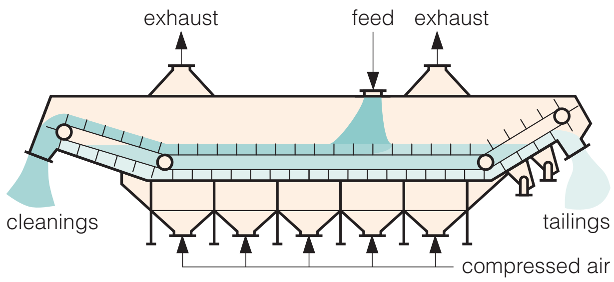

Figure 24 The schematic diagram of the ADMFB machine developed by CUMT (Katalambula and Gupta, 2009)

The first ADMFB plant was established by CUMT with an output of 320 kt/y and an efficiency E_p up to 0.05 at the Qitaihe Coal Dry Preparation Plant in northeast China in 1994 (Chen and Wei, 2007). Since then, new applications have been found and a 700 kt/y beneficiation plant was constructed for commercial testing. CUMT's Mineral Processing Research Centre has made efforts to beneficiate different size fractions of coal. A vibrated air-dense-medium fluidised bed was used for fine coal of size 6–0.5 mm; the ash content was reduced from 16.57% to 8.35%, with fuel recovery yield up to 80.20% and E_p value up to 0.065. A deep air-dense-medium fluidised bed was used to beneficiate >50 mm coal; An inefficiency value E_p up to 0.02 was achieved, suggesting that this process is suitable for waste removal from 300–50 mm large feedstock, particulary for large surface mines in China. A tribo-electric cleaning technology has been developed for <1 mm pulverised coal, yielding an low ash coal (<2%). Currently a pilot system with tribo-electric cleaning has successfully passed technical appraisal. In addition, a dual-density fluidised bed is being developed to optimise the product structure. Experimental results showed that using proper bed structure and operational parameters, two relatively stable beneficiation layers with differential densities in the axial direction were formed in the fluidised bed. Three products –clean coal, middlings and tailings – were produced simultaneously. The beneficiation results were also acceptable; the clean coal in the top layer had a density of 1.50–1.54 g/cm^{-3} with E_p of 0.06–0.09, while the density of the tailings was in the range of 1.84–1.90 g/cm^{-3} with E_p of 0.09–0.11.

7.2.6 FGX separator

The FGX separator is a proprietary dry coal processing technology developed by Tangshan Shenzhou Manufacturing Co Ltd (TSM), based in Tangshan, China. This dry deshaling technology provides an efficient gravity-based separation by combining an autogenous fluidised bed and a conventional table separator. The separating compartment consists of a deck, vibrator, air chamber and hanging mechanism, as shown in Figure 25. A centrifugal fan provides air that passes through the perforated deck at a rate sufficient to transport and fluidise the particles. The deck width tapers from the feed end to the final refuse discharge end. The coal is introduced into a surge bend and then fed onto the deck using an electromagnetic feeder. A coal particle bed of certain thickness is formed on the deck; the presence of about 10–20% under 6 mm material in the feed is needed to develop an autogenous fluidised particle bed. Low-density particles such as coal form the upper layer of bed, which are collected along the front length of the deck. Particles of sufficient density settle out from the fluidised bed of particles and report back to the deck surface. The heavy particles are then forced by both deck vibration and the continuous influx of new feed material to move in a helical transport pattern toward the narrowing end of the deck, where the final refuse is collected. The separation process generates three product streams: deshaled coal product, middlings and refuse tailings. There are presently ten models of FGX dry coal separators supplied by TSM, with capacity ranging from 10 t/h to 480 t/h. More than 800 FGX separators have been deployed in China, Indonesia, Mongolia, North Korea, South Africa, the Philippines, Ukraine, Vietnam and the USA.

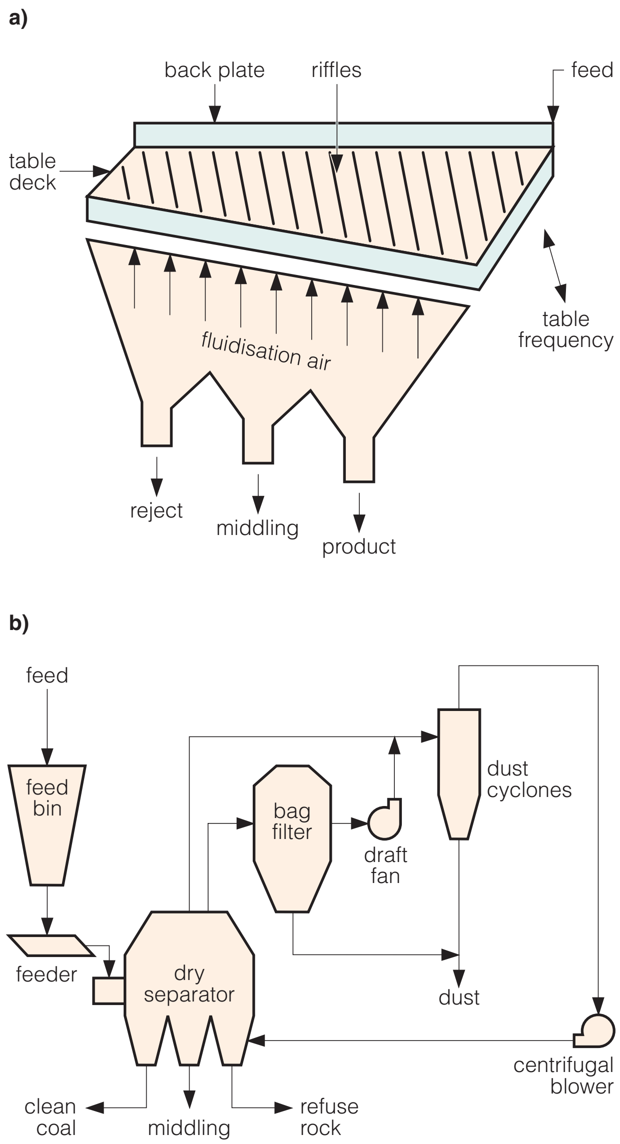

Figure 25 The schematic diagram and operation of the FGX dry coal separator (FGX SepTech, 2010)

Simplicity is one of the major features of FGX that boasts much lower operational costs than wet processes. One notable case is the Hanjiacun FGX coal preparation plant owned by China's Shenhua Group (FGX SepTech, 2010). This preparation plant treats <50 mm easy-to-wash coal using three FGX-48A separators to achieve a processing capacity of 1400 t/h. The quality of clean product from the FGX circuits at the Hanjiacun coal preparation plant can be sold directly onto the market, which generates significant economic return. FGX is also a favourable dry coal processing technology in cold and arid areas where any wet processing using large amounts of water is not feasible. For example, there is an FGX dry coal preparation plant at China's Xinjiang Mining Group which is located in a water-scarce area in western China. There are several FGX installations in Ukraine where temperatures become extremely low during winter.

The most important application of FGX separators is to deshale the run-of-mine (rom) coals. There is an increasing amount of rock in rom coal in many coal mines, both underground and surface operations, due to changing geological conditions. This usually results in increased haulage and processing costs, especially if the processing facility is far away from the mine sites. In this case, the FGX dry coal separator can be used for the deshaling purpose near a mine site or coal preparation plant. A considerable amount of extraneous rock can thus be removed from the rom coal prior to haulage and feeding to preparation plants, which in turn saves transporting and processing costs. Since the quality of deshaled product is much better than rom coal, the overall preparation plant productivity is improved. Improved feed quality also leads to reduced equipment wear, thus reducing maintenance costs significantly. Deshaling prior to feeding coal into a preparation plant also alleviates the problem of fine clay particle generation in wet processing. It is known that pyrite in shale is the major source of sulphur in some high sulphur coals. If the pyrite is well liberated, good separation can be obtained using FGX due to the fact that pyrite density is much higher than that of coal.

The FGX technology has been successfully applied at several lignite coal mines to beneficiate rom lignites. Due to its unique geological characteristics, mineral matter in lignite decomposes readily in wet processing, creating fine clay particles that can affect the water treatment systems of the wet preparation plant. In contrast, FGX does not involve the use of water, so is suitable for cleaning lignite. Trials have been done on separating a Texas lignite coal and the average total sulphur reduction rate obtained in the tests was 34.8%, which equates to an average SO_2 reduction of 35.8%. In addition, the mercury content of the FGX-treated lignite was found to decrease by about 50%. Tests were also made on Powder River Basin subbituminous coals with product yields approaching 90% and ash content less than 10% (Nunes, 2009).

Another application of the FGX separator is to recover valuable coal in some aged gob piles and even preparation plant refuse piles due to inefficient mining and processing methods employed years ago. For instance, a mining operation in Wyoming, USA, is estimated to lose 1–10 Mt/y of coal in the gob piles (Nunes, 2009). Recovering coal from these gob/refuse piles has become economically feasible due to the recent rise in coal prices. The low capital and operational costs of FGX by its nature makes it a favourable technical choice for recovering discarded coal from gob or refuse piles. Processing the aged gob/refuse piles also brings about environmental benefits because weathering of the piles can release harmful pollutants into the environment.

7.3 Chemical and biological cleaning processes

Current commercial practice in physical cleaning becomes increasingly inefficient and correspondingly more expensive as the particle size of pyrite decreases to the 50 µm and smaller range. Furthermore, physical cleaning of coal is ineffective in removing sulphur or other elements that are organically bound to the coal structure. These are the reasons for research efforts made in developing chemical and biological cleaning methods that have the potential for removing substantial amounts of both mineral and organic sulphur. Consequently, chemically or biologically cleaned coals could, in principle, be burned without requiring extensive use of the flue gas desulphurisation or other capital intensive additions to the coal combustion plant.

There are three broad groups of chemical cleaning methods. The first group is those that use elevated temperatures and pressures to oxidise pyritic sulphur to water-soluble sulphur compounds. An example is the TRW process that removes pyritic sulphur by leaching with aqueous ferric sulphate at moderate temperatures, pressures and long retention times. Mineral sulphur is converted to ferrous and ferric sulphates and elemental sulphur; the ferric ion lixiviant is simultaneously regenerated in the reaction chamber using oxygen. There are, however, no claims for removal of organic sulphur or inert mineral matter other than that associated with pyrite mineral forms. The second category of chemical cleaning processes use acid or caustic chemicals to leach pyritic and/or organic sulphur species from the coal matrix. The KVB process is one of this kind in which comminuted coal is heated in the presence of nitric oxide and other gases so that a significant amount of pyritic sulphur and some organic sulphur are removed as gaseous sulphur oxides. It is claimed that the reacted sulphur still remaining in the coal can be removed in subsequent steps by washing with water and/or a heated alkali metal hydroxide solution. The soluble sulphur compounds are mixed with lime to regenerate caustic and to precipitate gypsum for disposal. Those technologies that use a chemically-induced alteration of pyritic sulphur to enhance subsequent physical separation can be categorised into the third group. A good example is the Magnex process developed at Hazen Research Inc. In the Magnex process dry pulverised coal is exposed to vapours of iron pentacarbonyl ($Fe(CO)_5$ at, typically, about 193ºC and 0.28 MPa. The ion pentacarbonyl preferentially decomposes on the pyrite and other mineral matter rendering them magnetic. Therefore, these materials can be removed from clean coal by means of magnetic separation.

It should be pointed out that the development of chemical cleaning processes is mostly limited to the laboratory-test scale. The major reason is that extremely high processing costs, severe processing conditions, and safety and environmental concerns due to use of toxic gaseous or liquid reagents are not yet resolved. This significantly impedes the commercial success of these processes. There has been some work aimed to overcome some of these obstacles. For instance, the Environmental Research Center of the University of North Dakota has investigated extraction of organic sulphur and hazardous air pollutants using supercritical water (Timpe and others, 2001). The sulphur content and selected elements in some coals could be reduced by more than half by water at conditions above the critical temperature but below the critical pressure. Both bench-scale and pilot-scale tests have been carried out.

Biological coal cleaning processes also focus on the removal of sulphur. Various ‘sulphur bugs’ (micro-orgamisms) have been developed that attack the pyritic sulphur. Two families of micro-organisms have been found useful to remove pyritic sulphur from coal: thiobacillus ferro-oxidans and sulpholobus acidocaldarius. Another application of the thiobacillus ferro-oxidans is found in conjunction with the agglomeration process. Treating the coal with the micro-orgamisms apparently caused the pyrite to be rendered hydrophilic, so that pyrite can be rejected with tailings in the agglomeration cleaning process. However, the biggest disadvantage of biological treatment is the long reaction time, with weeks being required in some cases. While this may be impractical for coal that moves quickly from the mine to the boiler, some interest has arisen for application to long-term storage piles at power stations.

Most of the tests using either chemical or biological cleaning methods have been made on bituminous coals, since these coals are the predominant steam coals currently used in power plants. Little information is available on the effectiveness and attendant issues of application of these cleaning methods to low quality coals.

8 Conclusions

Low quality coals have a huge potential for providing an affordable and abundant energy resource for many decades. They are mainly used for power generation, in both PCC and CFBC power plants, as well as in several IGCC demonstration plants. Adoption of advanced steam conditions and scaling-up are the major challenges. Gasification-based applications, however, could be more valuable and flexible in product spectrum, which have become the focus of new technology development for low quality coals. Efficient coal drying is key to any utilisation routes for low rank coals; so is efficient cleaning for low grade coals.

PCC is the predominant technology for power generation from low quality coals. The effects of coal characteristics on combustion and PCC boiler operation are discussed in some detail. Subcritical PCC still dominates power generation using low rank coals, while supercritical PCC has been rapidly developed and deployed over the past decades. Currently, Germany possesses the most advanced lignite-fired supercritical PCC technology, BoA, which has been successfully demonstrated at the 1000 MW (gross) level by RWE with net cycle efficiency of 43.2% (LHV). Supercritical PCC units are also operational or under construction in Greece, Poland and the Czech Republic, though at a smaller scale. Advanced emissions control technologies, such as low NOx burners, SCR, FGD, activated carbon injection, are also incorporated on new plants to comply with stringent environmental regulations. In addition, more efficient pre-combustion drying technologies, such WTA, are also being tested on some plants. In China, although lignite-fired power generation accounts for a very small portion of the country's total coal-based generation capacity, it is of local importance in some northeastern and southwestern provinces. As a result, supercritical PCC units of 600–660 MW have been built in these regions, with almost all plant components supplied by China's domestic manufacturers. With interest in supercritical PCC technology revived in recent years in the USA, a few new units have been built to burn either lignite and subbituminous coals. It is noted that the John W Turk Jr Plant firing PRB subbituminous coal represents the first ultra-supercritical coal-fired power plant in the USA. Future development will concentrate on three major areas: large units, more advanced steam conditions, and CCS.

CFBC is a technology that, by the nature of its design, is well suited for combustion of low quality coals with good environmental performance. The effects of coal characteristics on coal combustion, the plant design and operation have been analysed. Asia (mainly China) is the largest market for CFBC, followed by North America and Europe. The 200–300 MW class is a mature technology for power generation, while scaling-up efforts by Foster Wheeler have led to the recently-commissioned 460 MWe supercritical Lagisza unit in Poland. Increasing the deployment of the 500–600 MW class supercritical units is the major focus of near-term development, while further scaling-up to 800 MW class is also being considered. Another focus of future development is the oxygen-blown operation or post-combustion CO_2 capture.

Three technologies based on coal gasification are discussed in detail. IGCC is a promising power generation technology with efficiency as high as 46–47% (LHV), very low emissions levels and high flexibility in products. However, the experience with coal-based IGCC is very limited as there are only six large-scale demonstration plant currently in operation. The IGCC experience involving low quality coal is even more limited. Strictly speaking, only the Puertollano IGCC plant and the Morwell IDGCC plant were built to demonstrate the viability of IGCC power generation using low quality coals or mixtures with other low grade fuels. It remains important for IGCC development to improve its availability and economics, while demonstrating its capability for large-scale CO_2 capture and storage.

Coal-to-liquids emerges as an important growth sector, which is projected to supply 1% of global oil demand by 2035. Current experience with indirect CTL is concentrated in the South African company, Sasol, which uses Lurgi moving bed gasifiers to convert about 30 Mt/y high ash coals to 150,000 bbl/d of liquid fuels. China is gaining significant experience in direct CTL through the 1 Mt/y Shenhua demonstration plant in Inner Mongolia, and aims to expand that capacity to 3 Mt/y. Moreover, four smaller indirect liquefaction projects also help strengthen China's position as a lead country in the development of CTL technology. There were a number of R&D projects on both direct and indirect coal liquefaction with the support from the US government in the 1980s through to mid-1990s. A significant outcome of these projects was to demonstrate that DCL was applicable to a wide range of coals including PRB subbituminous coals. In recent years, the interest in CTL revived due to USA's desire to wean itself off imported oil, which has led to 13 CTL projects under consideration of which five involve lignite or subbituminous coal. CTL is of great interest in Australia as it may increase the export opportunities for brown coals significantly. The major Australian developments include the Monash Energy CTL project in Latrobe Valley, Spitfire project in Western Australia, Hybrid Energy's FutureGas project in South Australia and Linc Energy's Chinchilla UCG-CTL project in Queensland. Japan, considering its security of energy supply and technology export market opportunities, is also actively developing direct CTL technology with partners in Australia and Indonesia. In Germany, a 3000 bbl/d lignite-fuelled project is planned at the Schwarze Pumpe site by Syntroleum and Sustec.

UCG has the potential to unlock vast amounts of energy present in coal reserves that are inaccessible using current conventional mining technologies. No commercial-scale UCG project has yet been demonstrated; developments in Australia and adjacent to the Majuba power plant in South Africa are probably closer to commercialisation than those elsewhere. In terms of seam depth and thickness, both trials are being carried out in relatively favourable circumstances. It is likely that the first commercial-scale UCG operation could start up within the next decade.

Some prospective technologies for drying of low quality coals are described. Geographically, development of these drying technologies has concentrated in Australia, Germany and the USA, and to a lesser extent in Japan and Indonesia. The majority of the development efforts have been placed on evaporative drying processes. This is a natural extension of the conventional evaporative drying processes, such as flash mill drying or steam tube drying, which are now widely used in power plants or coal briquetting facilities. Amongst these evaporative drying processes, WTA and DryFining™ have reached the stage of large-scale demonstration. WTA and DryFining™ are very close to commercial deployment in lignite-fired power plants for pre-drying the coal feedstock. LLD drying process, Coldry™, Drycol®, DevourX mill, LamiFlo™, Alligrator mill and superheated steam drying have the potential for upgrading low rank coal for export or transport to distant users. This is of particular importance to countries or regions with vast local low rank coal reserves, such as Indonesia and the State of Victoria in Australia. Another intriguing notion is that some technologies, conventionally used for drying either agricultural goods or minerals, are now being adapted for drying of low rank coal. This indirectly indicates the current move in the coal industry worldwide. Non-evaporative drying technologies have emerged due primarily to their lower energy consumption per mass unit of water removed. However, this potential benefit comes with a daunting disadvantage, the remediation of wastewater produced. Contamination of the product water with both organics and inorganics makes its remediation so costly that many development interests in Australia, Germany and Japan have been discouraged. Finding a cost-effective approach for remediation of the product water is a key step towards the commercial implementation of the non-evaporative drying technologies. In addition, another necessary step is the improvement to the batch-process operation. The commercial success of non-evaporative drying technologies is hinged on whether the system can work in a fully-automated continuous operation.

Briquetting and integrated coal upgrading technologies incorporate drying as an important component. Briquetting is a relatively simple and long-used method for upgrading low rank coal or coal fines into a cleaner and transportable solid fuel with improved strength. There are large briquetting plants in the USA and Germany, while Australia has significant experience in binderless briquetting of brown coal and has expanded operation (of White Energy) to Indonesia, the USA, China and South Africa. Although China has a large number of briquetting plants, these plants use old briquetting technologies and their products are of low quality. Coal briquetting remains of only local importance and there is a lack of established markets for coal briquettes. Advanced coal upgrading technologies, including K-Fuel®, UBC®, Syncoal®, Cowboy Coal Process, and CCI process, are also discussed. These technologies have reached either pilot scale or commercial demonstration scale with projects undertaken in Indonesia, the USA and China. They hold the potential for increasing the export or remote domestic market opportunities for low rank coals.

Coal cleaning technologies enable cleaning of run-of-mine coals prior to their combustion in boilers and recovering lost coal from mine gob piles. Wet cleaning processes are generally not economically applicable to low rank coals due to the close specific gravity of coal substance and mineral matter in these coals, their easy-to-breakup weak strength, and troublesome surface properties. Dense-medium separation may be possible for some lignites if fines generation is not very severe. Although dry coal cleaning technologies are historically less widespread than wet cleaning processes, they seem promising for cleaning low quality coals. The low capital and operational costs of dry cleaning technologies may justify cleaning of these low-priced coals to improve their quality and ultimately to increase their utilisation. Chemical and biological cleaning technologies are also briefly introduced. However, their application to low quality coals have been and will remain low for years to come due to their high costs, environmental and safety concerns.

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