Chapter 6
Clean Coal Technologies for Power Generation

6.1 Importance

In present day world fossil fuels are the major resource for power generation. For example, in India coal makes up 55 %, natural gas 10 %, hydroelectric 26 %, renewable 5 % and nuclear 3 % of total installed capacity. In UK almost half of the nation's electricity is generated from gas with a further 28 % coming from coal. In fact, coal is the most abundant fossil fuel and has long lasting reserves. Its availability is domestic in several countries and has exhibited stable prices. The world coal reserves of approximately 1040 billion tonnes may last for more than 200 years. In view of discussion in Chap. 5, coal is considered the most polluting fuel in the countries' energy mix. It has more than 40 % mineral matter (ash) content posing problems in handling, transporting and using the fuel in power plants. Some 20 % of the power plants in UK and India are old and below the margin of environmental safety and they are due for technology amelioration. Present day researchers are working to make existing coal technologies cleaner and affordable to enable a transition to green power generation. In what follows we present an outline of clean coal technologies.

6.2 Environmental Issues

Health related problems were the earliest documented hazard due to coal-based power plants. The tall stack concept was implemented to dilute the concentration. It was followed by the identification of several phenomena and related local and global environmental concerns which may be classified into three categories as follows:

1. Enhanced greenhouse effect due to carbon dioxide (CO_2) and Nitrous oxide (N_2O).

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2. Smoke and acid rain effects of SO_x and NO_x.
3. Health related problems due to suspended or respirable particulate matter, SO_x, NO_x and trace elements like arsenic and mercury.

Greenhouse effect has received increased attention since 1980s. Coal's contribution to enhance greenhouse effect is about 20 %. The contribution is much less due to methane CH_4 (7 %) and N_2O (5 %) which have accumulated in the atmosphere due to various agricultural activities like wet paddy fields, decomposition of vegetation, agro waste disposal, biomass burning and leakages from coal mining and gas pipelines. However, it may be noted that the global warming potential of CH_4 is about 15–17 times, N_2O is 280–310 times and of chlorofloro carbons (CFC) about 7900–8500 times that of CO_2 (Kolar and Reddy 2004).

6.3 Emission Control in Power Plants

Several devices and techniques for the control of pollution resulting from coal utilisation in power plants have been proposed and tested and are presently in use. These include pre-combustion controls, combustion control, post combustion control and atmospheric dilution. These are summarised as follows:

6.3.1 Pre-combustion Controls

Coal is predominantly aromatic and is one of the most carbon intensive amongst the fossil fuels. Coal from different mines has different ash, moisture and mineral contents. Pre-combustion control of pollution involves measures to obtain better and less polluting coal fuel. According to New Source Performance Standard (NSPS), emission of SO_2 in coal plants is restricted to 1.2 lb/Mbtu (520 g/10^6 kJ). The coal which meets this emission rate without controls is referred to as compliance coal or low sulphur coal. An obviously effective technique could be homogenisation and blending to obtain relatively better and cleaner fuel. To control sulphur emissions high sulphur content coal may be substituted with low sulphur content coal or with the blend of two. The approach is referred to as fuel switching and can reduce SO_2 emission from 30 to 90 %. The other pre-combustion approach currently used is beneficiation of coal to get rid of unwanted mineral matter contents and other micro constituents. It involves the removal of sulphur in which the coal is either bound into organic coal molecules or in the form of inorganic pyrite (FeS_2). The physical coal washing may be used to wash away FeS_2 having 3.6 times greater specific gravity than coal. Desulphurisation of coal may also be carried out by organo-solvo refining. This technology is still at the research stage.

The coal washing process also reduces the ash contents and increases the calorific value of the fuel which in turn reduces the coal transportation and pulverization costs. The sulphur bound in organic molecules of the coal may be removed by chemical and biological methods and is referred to as refining of coal. For example, organo-solvo refining wherein solvent extraction of impurities yields super clean coal with low ash. This technique is also in the research stage.

6.3.2 Combustion Control Techniques

Diverse range of approaches and technologies are needed to minimise emissions of carbon dioxide from the use of coal in power plants. The obvious approach is to improve the method of energy extraction from coal in its combustion in a furnace cum boiler of a power plant. In the conventional system coal is used in the pulverised form, its size being less than 100 μm. The approach is referred to as Pulverised Combustion (PC) Firing or PC Technology. The combustion efficiency of PC boiler is about 99 % and the thermal efficiency (boiler efficiency) is of the order of 80–90 %. The major drawback of PC technology based power plants is that it has very low energy efficiency (<40 %) and enormous amounts of undesirable gases (SO_x, NO_x, CO_x and N_2O) are exhausted. Fluidized Bed Combustion (FBC) is a promising technology in this regard. The basic characteristics of this technology are as follows:

- Combustion chamber contains finely divided particles such as sand.
- Combustion air entering from below lifts these particles until they form a bubbling bed.
- Start-up burners heat the bed to 800–950 °C. Subsequently, combustible material (crushed fuel top size is 6 mm) is fed into the bed. It ignites almost immediately.
- FBC can burn large varieties of fuels from high rank commercial fuels to low grade and waste fuels.
- For small scale power generation generally bubbling FBC are used. However, for large scale FBC due to deeper fluidized bed circulating FBC boilers are used. These are the conventional boilers. They operate at atmospheric pressure and therefore are often referred to as atmospheric FBC (AFBC) boilers.
- Yet another variant of FBC is based on pressurised 15 atm operation and is referred to as Pressurized FBC (PFBC).
- Both AFBC and PFBC work on two fundamental gas-solid dynamics: the bubbling or circulating as illustrated in Fig. 6.1a, b.
- All the four variants of FBC family are efficient and clean. However, the AFBC based circulating bed system exhibits cleaner performance than the bubbling bed.
- Pressurised FBC (PFBC) are used to heat gas which can be expanded through a gas turbine and can be used in a combined cycle based plant. Both the AFBC and PFBC can yield high overall plant efficiency of about 43 % as compared to 33–37 % of conventional CFBC and AFBC based power plants.

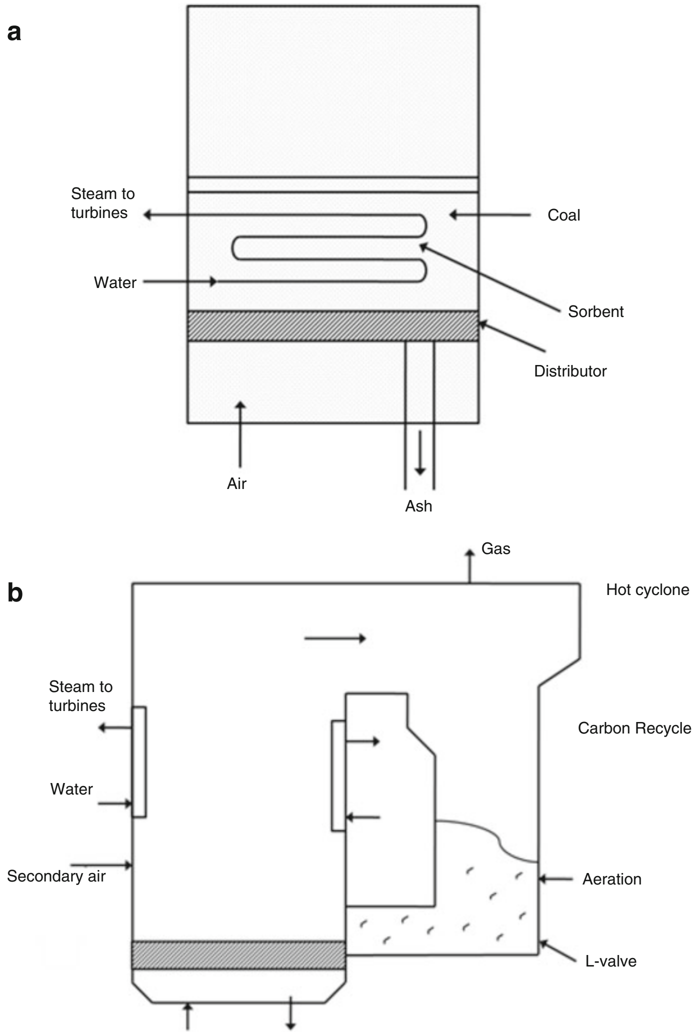

Fig. 6.1 (**a**) Bubbling fluidised bed boiler. (**b**) Circulating fluidised bed boiler

- In view of the above discussion Pressurized Circulating Fluidized Bed Combustion (PCFBC) based power plants are ultimate in terms of efficiency and environmental considerations.
- Yet another alternative to direct coal combustion is coal gasification wherein coal is reacted with steam and air/oxygen in a reactor at suitable pressure and temperature to produce a gaseous mixture of carbon monoxide, hydrogen, methane and CO_2 known as syngas (synthetic gas) which can be burnt in a gas combustor.
- For sulphur removal FBC boiler fuel is mixed with limestone ($CaCO_3$) or dolomite ($MgCO_3.CaCO_3$); ($MgCO_3$ does not take part in the reaction).

Generally 3.15 kg of $CaCO_3$ is mixed for 1 kg of sulphur removal. The crushed mixture is held in suspension (fluidized) by the air stream injected from the bottom of the bed. Sulphur oxide released during combustion reacts with the limestone to form solid calcium sulphate as follows:

$$CaCO_3 + SO_2 + \frac{1}{2}O_2 \rightarrow CaSO_4 + CO_2 \quad (6.1)$$

If the temperature exceeds the equilibrium value, the endothermic reaction proceeds as follows:

$$CaCO_3 \rightarrow CaO + CO_2 \quad (6.2)$$

$$CaO + SO_2 + \frac{1}{2}O_2 \rightarrow CaSO_4 \quad (6.3)$$

Thus, sulphur of the fuel is removed in the form of solid calcium sulphate, which falls to the bottom of the furnace and is removed. There are processes for regeneration of lime for reuse as the additive. However, the present economics often indicate a preference for once – through limestone system.

In FBC boilers, sulphur removal rates can be higher than 90 %. The heat transfer from the combustion region to the boiler tubes is also more efficient because fluidized particles are in direct contact with boiler tube and heat is transferred by conduction rather than by less efficient convection and radiation. The higher heat transfer efficiency enables the boiler to operate at about half the temperature ($\approx$700–800 °C) of conventional boilers temperature (1400–1600 °C). This greatly reduces the formation of NO_x. In FBC boilers, coal with higher ash content can also be burned without fouling the heat exchanger, since the operational temperature may be kept below the melting point of ash.

Operating experience with the FBC systems has shown that their emissions often show values lower than the stringent present-day world over norms of 650 mg/Nm^3. However, further reduction of NO_x is possible through the techniques as follows:

(i) *Low Excess Air Technology:* Wherein the amount of air made available for combustion is controlled to the minimum amount required for complete combustion.
(ii) *Second Generation Low NO_x Burner:* It involves two stages of air feed: In step 1 due to starvation of air, CO is formed, N_2 is released and in the other stage complete combustion takes place.

6.3.3 Post Combustion Technologies

Stack emissions from a coal-based power plant consists of fly ash as a particulate matter and oxides of nitrogen, carbon and sulphur as gaseous pollutants. The emissions from oil and gas fired plants consists of only gaseous pollutants. In older power plants cyclone type mechanical dust collectors were used. Presently, electrostatic precipitator (ESP) is the main choice as fly ash collector. As electrostatic precipitator is basically a system wherein gaseous particles which are charged to saturation and collected on electrodes. ESP is available for both horizontal as well as vertical gas flows. Yet another device used for post-combustion pollution control is fabric filter, it is by far the most efficient collector of fly ash and is used in industries. In fabric filter the dust laden gas is passed through a suitably shaped fabric resulting in the deposition of dust on the fabric. The quality of fabric now determines the performance of bag filters. Fabrics like fibre, glass and teflon are capable of withstanding higher temperatures (up to 250) and resist chemical erosion and are therefore, often used in fabric filters.

6.4 Clean Power Plant Configurations

The above techniques used individually or in tandem evolve several power plant configurations as follows:

(i) Plant with conventional PC firing in Rankine cycle power plant with Fuel Gas Desulphurisation (FGD), and particulate control.
(ii) Plants with Atmospheric Fluidised Bed (AFBC) boiler in Rankine cycle.
(iii) Circulating Fluidised Bed (CFBC) boiler with Rankine cycle.
(iv) Combined cycle power plant with Pressurised Fluidised Bed (PFBC).
(v) Integrated Gasifier Combined Cycle Power plant with steam based heat recovery system.

The configurations 1, 2, 3 are commercially well proven. The configuration 4 is in the initial stages of commercialisation and 5 is at R&D demonstration stage.

6.4.1 Integrated Gasification Combined Cycle (IGCC) Power Plant

As the name implies, this power plant consists of a coal gasifier whose product gas ($CO + H_2 + CH_4$) with a calorific value of 4–7 MJ/Nm^3 is cooled in the gas cooler and then cleaned (to remove H_2S, COS and particulate matter) in a Gas Clean Up (GCU) system before being introduced into the combustor of a gas turbine. The hot gases from a combustor at a temperature of up to 1250 K are expanded in the gas turbine to generate electrical energy. The exhaust gases from the gas turbine which are still at a considerably high temperature are made to generate steam in a Heat Recovery Steam Generator (HRSG). The high temperature high pressure steam is sent to turbo generator for the production of electricity. The exhaust gases from HRSG are let out to the atmosphere with additional heat recovery in an economiser.

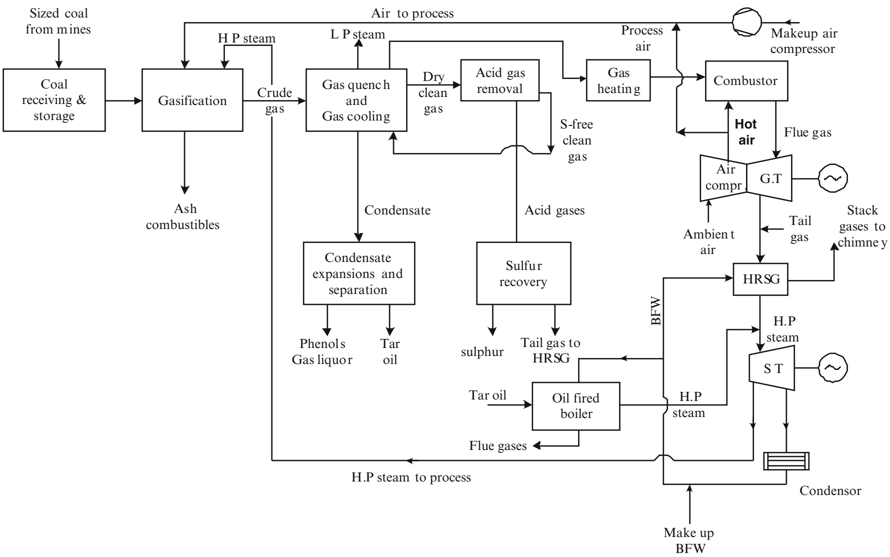

Fig. 6.2 Flow diagram of conceptual 600 MW IGCC plant (Kolar and Reddy 2004)

The combined cycle operation of using the gas turbine and the steam turbine results in an overall plant efficiency between 39 and 45 % and has potential of achieving close to 50 % in the future. Further as the gas is cleaned before it is combusted the amount of gaseous and particulate pollutants in the exhaust gases is very low. In fact it has been well established that presently this is the most environmental-friendly technology for coal utilisation. In India, the Indian Institute of Chemical Technology, Hyderabad has been developing coal gasification technology since 1983. It has a 24 tonnes/day pilot plant on which various Indian coals have been studied. Based on this experience, IICT has developed a conceptual design of 600 MWe IGCC plant which has been illustrated in the Fig. 6.2 (Kolar and Reddy 2004).

Reference

Kolar, A.K. and K.S. Reddy (2004). Advanced Energy Technologies, AICTE-ISTE Short Term Course, pp. 73–110.