further, coal power plants will have to move progressively away from steam-based systems toward advanced generation cycles centered around coal gasification technology. A new line of integrated gasification power plants incorporating advanced gas turbines or molten carbonate fuel cells is expected to boost efficiency well beyond today's level of around 37%--efficiency may approach 60% by the year 2020. When fully realized, these advanced plants will coproduce electricity and such valuable chemicals as hydrogen, methanol, and gasoline, while nearly eliminating air emissions and solid wastes."

1.2 ENTRAINED BEDS

1.2.1 Combustion

(i) *Processes.* Combustion of pulverized coal in entrained or suspended beds in utility and industrial boilers is by far the most common method of coal use. The run-of-mine coal is crushed, dried, and pulverized to fine powder in a crusher and a pulverizer or mill. Typically, 70 to 80% of the pulverized coal particles pass through a 200 mesh sieve of 74 μm apertures. The pulverized coal is transported with a small part of the total air needed for combustion, the primary air, to a burner and into a furnace. A greater part of the total air, the secondary air, is heated and introduced through the burner ports into the furnace to ensure complete combustion. The combustion rate of the pulverized coal is very high because of the greatly increased pulverized coal surface area. The pulverized coal particles are entrained by the combustion air and transported in suspension through the furnace. They devolatilize, ignite, and burn leaving ash; the residence time of the pulverized coal particles in the furnace is typically 1-2 seconds and usually sufficient for nearly complete combustion. However, some of the very largest particles, that can be 400-500 μm in size, do not always burn out (ref. 33). A large proportion of the ash leaves the furnace still entrained as fly-ash and must be removed in an electrostatic precipitator. Some ash deposits on the tubes in the furnace and in the flue gas passages, causing slagging and fouling. The remaining ash falls to the bottom of the furnace and is removed through an ash hopper.

To dry coal and increase the furnace temperature, the secondary combustion air is often preheated in an air heater. Sometimes, for very reactive, high-moisture coals, a part of the hot gases is removed after the furnace and used, instead of the primary air, to dry and transport the pulverized coal.

Pulverized coal combustion is associated with the formation of pollutants like SO_2, NO_x, particulates, and others (see Chapter 6). However, the formation and emission of pollutants can be controlled and reduced to the acceptable levels. Today, the sulfur oxides are usually removed in the flue-gas-desulfurization units, FGD, often called wet scrubbers. The nitric oxides formation is reduced by the low-NO_x burners and the particulates are removed in the electrostatic precipitators. Pollution control

systems for pulverized coal plants account for as much as 40 % of capital and 35 % of operational cost (ref. 34). Tomorrow, advanced clean coal technologies will reduce the formation and emission of pollutants even more and in many cases more efficiently and less costly than technologies available today.

The main advantages of pulverized coal combustion are: high reliability, full automation, adaptability to all coal ranks, and excellent capacity for increasing unit size. The main disadvantages are: high energy consumption for pulverizing coal, high particulate emissions, and SO_2 and NO_x emissions.

Combustion of pulverized coal particles has several stages: heating and drying coal particles, releasing volatiles, forming char, igniting and burning volatiles and char (see Chapter 3). The most time-consuming is usually char combustion. The heat of char combustion is 95% of the total heat of combustion for anthracite and not less than 40% of the total heat of combustion for highly volatile peat. The time for char combustion is typically 90% of the total time for combustion. For high moisture coals, drying may also be a very important process.

The main process in pulverized coal combustion is heterogeneous chemical reaction of carbon from coal with oxygen from air to produce carbon dioxide and carbon monoxide:

$$C + O_2 = CO_2 \tag{1.1}$$

$$C + {}^{1}/_{2}O_2 = CO \tag{1.2}$$

There are also other heterogeneous and homogeneous chemical reactions such as homogeneous, gaseous combustion. All of these chemical reactions are greatly influenced by several physical processes:

1. the turbulent flow of the pulverized coal and the air through the burners and into the furnace; the swirling flow in the proximity of the burners or in the furnace;
2. the turbulent and molecular diffusion and the convective mass transport of gaseous reactants and products in homogeneous gas reactions and heterogeneous gas-coal reactions; particle dispersion;
3. the convective heat transfer through the gas as well as between the gas and the coal particles; the convective transfer of the heat of combustion;
4. the radiative heat transfer between the gas and the coal particles and between the coal/air mixture and the furnace walls.

Pulverized coal combustion is a complex process consisting of many interdependent chemical and physical processes.

(ii) *Technologies.* There are many pulverized coal combustion technologies available today. Most components are common to all pulverized coal combustion technologies and in this section some will be described such as crushers, pulverizers, transport systems, burners, furnaces, and pollution control systems.

There are several types of crushers commonly in use: Bradford (rotary) breakers, single- and double-roll crushers and hammer mills (refs. 27, 35-37). The Bradford breaker , for example, breaks the coal by the force of gravity. It consists of a large, slowly rotating cylinder typically 2.7 to 3.7 m (9 to 12 ft.) in diameter and 6.1 to 9.1 m (20 to 30 ft.) long, rotating at approximately 20 rpm. The cylinder is made of perforated steel plates and radial shelves. The size of the perforations determines the size of the crushed coal: typically these openings are 3.2 to 3.8 cm ($1\frac{1}{4}$ to $1\frac{1}{2}$ in.). The coal is fed at one end of the cylinder and carried upward on the radial, lifting shelves until it drops and breaks. The production of fines is small. The coal broken to the size of the perforations passes to a hopper below. Larger refuse and tramp iron are discharged at the end of the cylinder. The Bradford breaker, probably the most commonly used crusher for large capacities (ref. 36), is shown in Fig. 1.5.

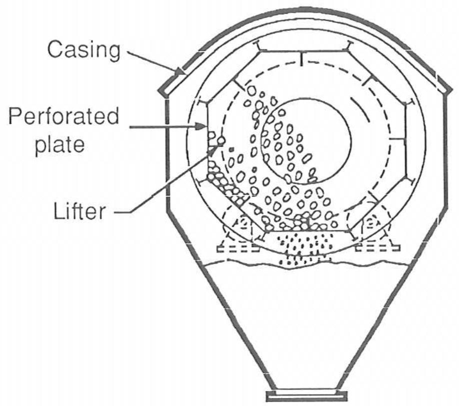

Fig. 1.5 Bradford breaker (published with permission from ref. 27).

A pulverizer or mill grinds, dries, classifies, and delivers the coal to a transport system. Pulverizers can be classified as low, medium, and high speed machines. The low speed pulverizers include the ball or tube mills and the large roll-and-race and ball-and-race pulverizers used in utility plants. The medium speed roll-and-race and ball-and-race pulverizers are used mostly in industrial and in some utility plants. The high speed impact or hammer mills and the high speed attrition mills are used in both industrial and utility plants. All of these machines grind by impact, by attrition, by compression, or by a combination of two or all of these forces. The main types of coal pulverizers and their specifications are listed in Table 1.12.

The medium speed roll-and-race and ball-and-race pulverizers are the most commonly used pulverizers (ref. 36). The grinding takes place by crushing and attrition of the coal between two surfaces, one rolling over the other. The rolling elements may be balls or rolls rolling over a race or a ring. There are two classes of

these mills. In one, the roller assemblies are driven and the ring is stationary. In another, which is used more often, the ring rotates and the roller assembly is fixed. Such roll-and-race pulverizer, also called the bowl mill, is illustrated in Fig 1.6.

TABLE 1.12

Comparison of leading pulverizer types (published with permission from ref. 27)

	Pulverizer Type			
Item	Ball	Ball-and-race	Roll-and-race	Attrition
Pulverizing method	Impact, attrition	Crushing	Crushing	Impact, attrition
Speed,rpm	15-25	90-200	20-105	900-1800
Capacity, tons/hr	5-160	2-20	2-105	3-30
Coal top-size, cm	1.9 ($\frac{3}{4}$ in.)	3.8 ($1\frac{1}{2}$ in.)	2.5-5.1 (1-2 in.)	6.4 ($2\frac{1}{2}$ in.)
Fineness (through 200 mesh sieve), %	70-95	70	65-85	70-95
Key applications	L util[a]	S,M,L ind[b]; S,M util[a]	M ind L util	S,M ind
Main advantages	Low maintenance, high reliability	Compact, low capital cost, accommodates many coals	Low maintenance, low vibration, capacity over wear cycle	Compact, rapid response to load changes, quiet operation
Main limitations	Large space requirements, noisy, high power consumption	High maintenance cost, low capacity	Outlet temp 372 K max, air/fuel ratio depends on grindability, moisture limits	High maintenance costs with abrasive coals

[a]S, M, L util. = small, medium, large utility.
[b]S,M,L ind. = small, medium, large industrial.

The high speed impact or hammer mills are used commonly in Europe for lower rank coals of high moisture content (up to 50%) (ref. 35). The hot gases from the furnace are recirculated into the pulverizer to dry the coal. The fineness of the pulverized coal is much less than 70 to 80% through a 200 mesh sieve (74 μm openings), typical in American practice.

There are two main types of the pulverized coal transport systems: the storage system and the direct system. In the storage system, the pulverized coal is separated from the transport air or gas and stored in a bin. The pulverized coal is discharged from the bin as needed and transported by the primary air to a burner. The storage

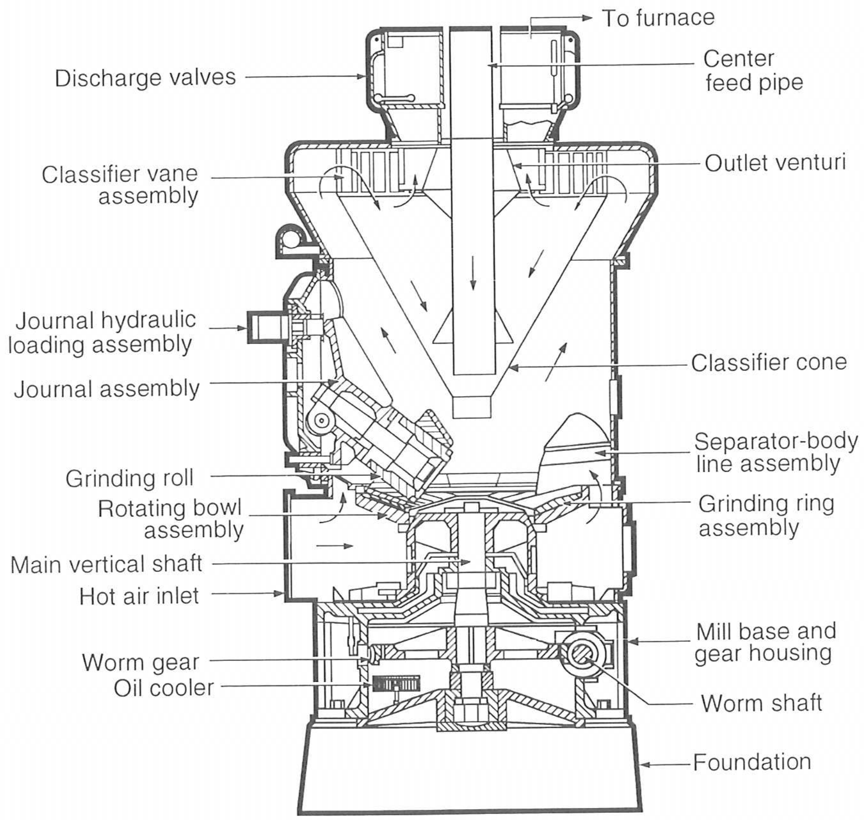

Fig. 1.6 Bowl mill (published with permission from ref. 36)

system has been largely superseded by the direct system. In the direct system, the coal is transported to the burner directly. This system is simpler and safer. The quantity of the pulverized coal in the system is smaller and the fire hazard is reduced.

The pulverized coal burners are of two main types: the swirl burner and the jet burner. Other types are variations of these two basic designs. In the swirl burner, the coal and primary air as well as the secondary air are introduced into the furnace with a strong, swirling rotation. The swirling motion of the air and the appropriately shaped burner throat give rise to a low pressure region close to the burner throat. The hot combustion products recirculate back toward this low pressure region and provide the ignition energy needed for stable combustion. The recirculation zone can extend several throat diameters into the furnace; ignition takes place mostly within this zone. Each burner is largely independent and has its own flame envelope. The degree of

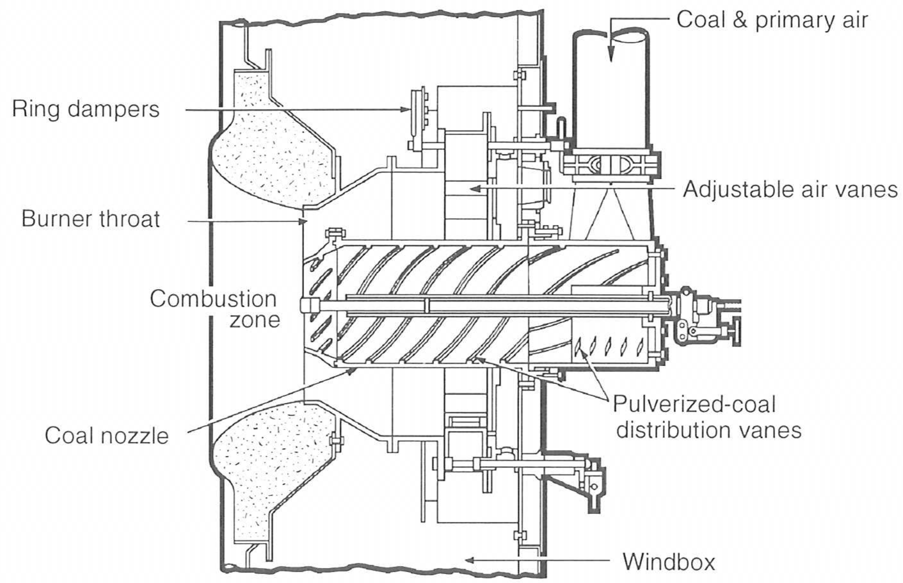

Fig. 1.7 Swirl burner (published with permission from ref. 36).

interaction between the burners is limited and depends on the the burner and furnace configurations (ref. 36). A swirl burner for wall firing is shown in Fig. 1.7.

In the jet burner, the coal and primary air, as well as the secondary air, are introduced into the furnace as jets with no rotation. The jet burners are often placed at the corners of the furnace so that the coal and air jets are tangential to an imaginary vertical cylinder at the center of the furnace. This gives rise to a rotation of the large mass of gases in the center of the furnace, referred to as the fireball. The jet burners operate together and have a single flame envelope (ref. 36). A jet burner for corner firing is illustrated in Fig. 1.8.

The pulverized, coal-fired furnaces are usually classified, according to the method of ash removal, into dry-ash and molten-ash furnaces. The dry-ash furnaces are also called the dry-bottom furnaces while the molten-ash furnaces are called the wet-bottom furnaces or the slagging-bottom furnaces (refs. 36, 38).

The dry-ash furnaces are much more common in the United States than the molten-ash furnaces. They are simpler, more flexible, and more reliable. However, they are also larger for the same capacity and most of the ash leaves the furnace still entrained as fly-ash; the fly-ash must be removed in the electrostatic precipitator or baghouse filter. The most commonly used dry-ash furnaces and burner configurations, shown in Fig. 1.9, are horizontal, opposed horizontal, tangential, opposed inclined, single U-flame, double U-flame and vertical.

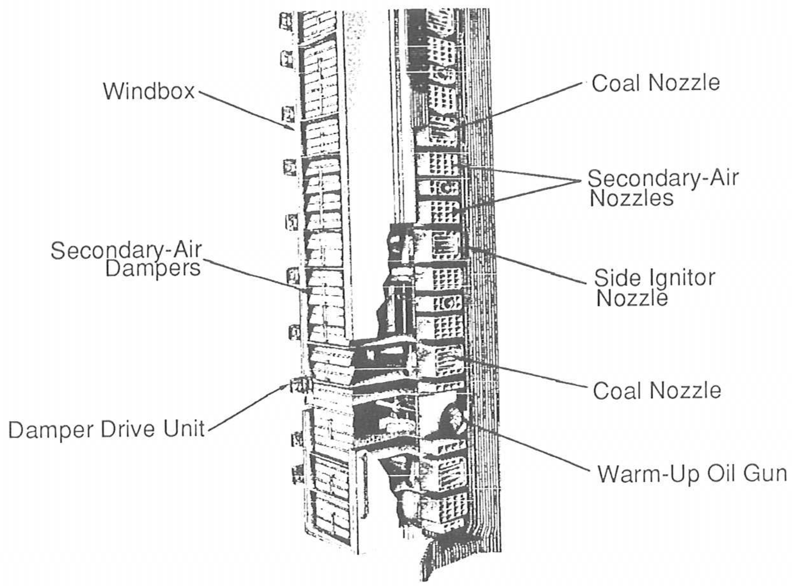

Fig. 1.8 Jet burner (published with permission from ref. 36).

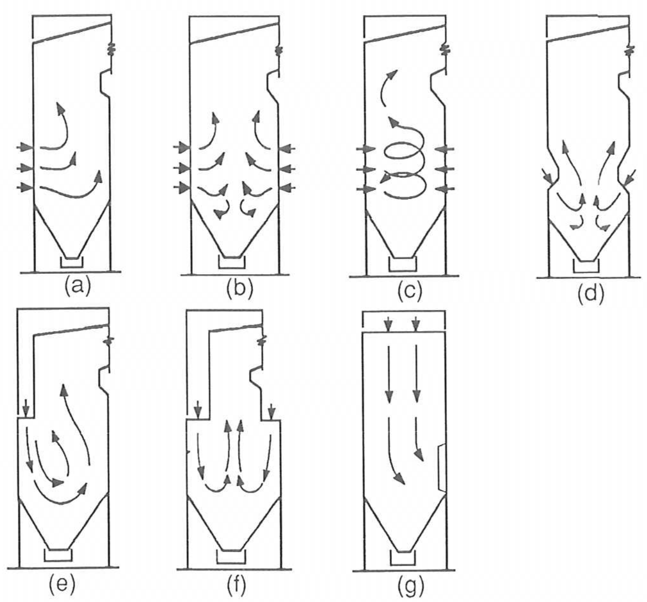

Fig. 1.9 Dry bottom furnace and burner configurations: (a) horizontal (front or rear), (b) opposed horizontal, (c) tangential, (d) opposed inclined, (e) single U-flame, (f) double U-flame, and (g) vertical (published with permission from ref. 38).

The horizontal, Fig. 1.9a, and the opposed horizontal, Fig 1.9b, configurations are usually fired by the swirl burners placed in the front or rear wall or both. Each burner is independent and has its own flame envelope. The tangential or corner-fired furnaces, Fig. 1.9c, and the opposed, inclined furnaces, Fig. 1.9d, are fired by the jet burners. In such furnaces there is a single flame envelope. The single U-flame and double U-flame firing methods are used for fuels hard to ignite and burn such as anthracite and coke. The vertical firing, Fig. 1.9g, is used for small units but not frequently. Figure 1.10 shows a 256 MW subcritical drum-type boiler for burning pulverized subbituminous coal (ref. 36). The jet burners are located at five elevations in the four corners of the furnace for tangential firing.

In the United States, most boilers installed during the 1980's have been of the 18 MPa subcritical drum type. These boilers will probably continue to dominate the utility market in the 1990's with the expected unit sizes between 300 and 400 MW or larger. The supercritical, once-through boilers will challenge the drum boilers only in very large sizes-800 MW and above (ref. 27).

The molten-ash furnaces are used more extensively in Europe (ref. 38). The molten-ash (the slag) flowing from the furnace is quenched by water and reduced to a coarse, granular solid. The furnace ash retention is very high: more than 80% is retained in some designs. The heat release rates are also very high and result in smaller furnaces. The cyclone furnaces, even though based on the molten-ash removal, are usually not classified as entrained bed furnaces. In the cyclone furnace, a large portion of the coal is burned on the surface of a moving slag layer.

Pulverized coal combustion is associated with the formation and emission of pollutants but both may be controlled and reduced to acceptable levels. Pollutant formation and control are discussed in detail in Chapter 6. The pollutant control technologies are commonly divided into pre-combustion, combustion, and post-combustion technologies. A list of the technologies, commercially available or in the final stages of development, is shown in Table 1.13.

The most significant pollutants from pulverized coal combustion are SO_x, NO_x, and particulates. There is a range of technologies for controlling the SO_x formation and emission: firing of low sulfur fuel, coal cleaning, control during combustion, and post-combustion flue gas desulfurization (FGD). The most widely used technology is flue gas desulfurization; it is a highly efficient but also very expensive technology. More than 100 FGD technologies are commercially available or under development world wide (ref. 39). They are usually classified as: wet throwaway FGD, dry throwaway FGD, and regenerative FGD. By far the most common FGD technology is the wet throwaway or the wet scrubbing. The largest user of FGD in terms of installed capacity is the United States with over 80,000 MW, followed by Japan with about 45,000 MW, and Germany with about 40,000 MW (ref. 39). The FGD systems are required on all new coal-fired power plants in the United States. The first wet scrubbers used lime as a sorbent and produced waste requiring disposal. Most new

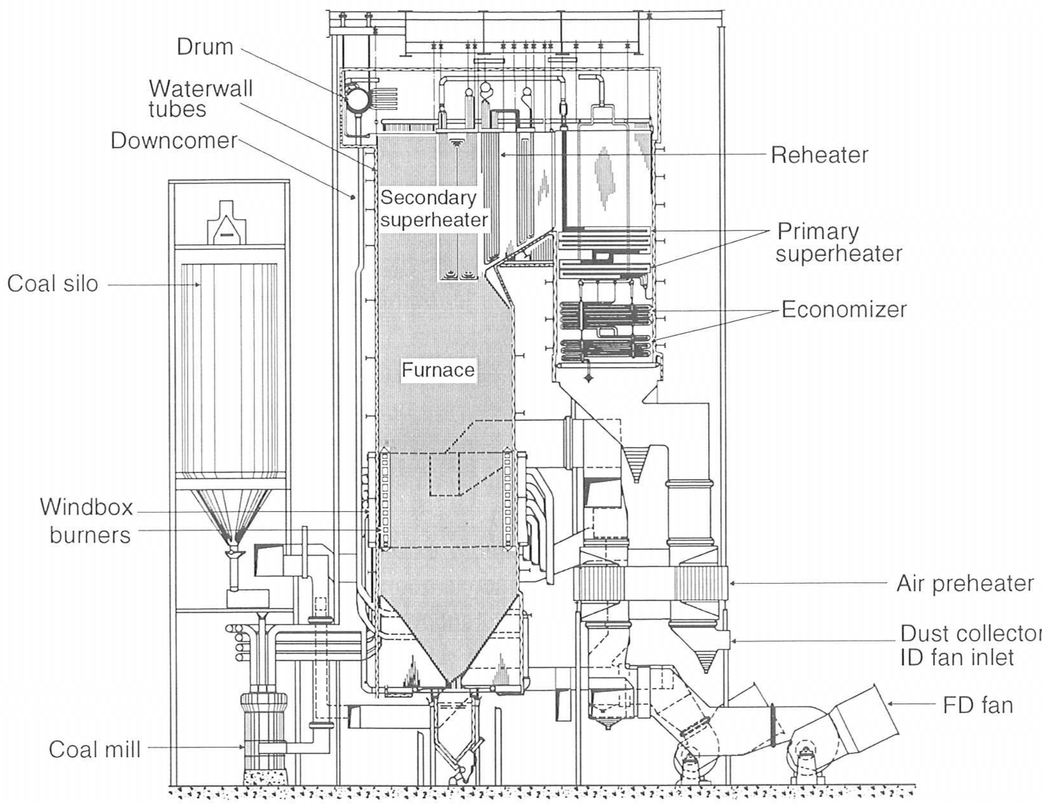

Fig. 1.10 Tangentially fired boiler (published with permission from ref. 36).

wet scrubbers use limestone and produce gypsum which can be marketed. In the wet scrubber, the flue gas passes through an absorber tower at low velocity while being sprayed by the limestone slurry. A spray tower absorber is shown in Fig. 1.11.

There are two broad groups of the NO_x control technologies: combustion and post-combustion. Low-NO_x burners, flue gas recirculation, natural gas or coal reburning, ammonia injection and other methods seek to reduce the NO_x formation or emission during combustion. Selective catalytic reduction (SCR), selective non-catalytic reduction (SNCR), flue gas treatment, and others are post-combustion technologies. Among these technologies, the low-NO_x burners are the most commonly used; the low-NO_x burners reduce NO_x concentrations by 40 to 65 percent compared with conventional burner design. These burners modify the pulverized coal and air flow patterns to reduce the oxygen concentration in the region of the fuel NO_x formation and to reduce the flame temperature in the region of the thermal NO_x formation. There are two main types: the dual register and the distributed mixing

TABLE 1.13

Pollution control technologies (published with permission from ref. 27)

PRECOMBUSTION OPTIONS Physical coal cleaning ▪Ash ▪Pyritic material Chemical coal cleaning Fuel-oil preparation ▪Settling ▪Salts removal ▪Blending Fuel-oil emulsification Chemical additives Gasification/lique-faction Other fuel conversions Coal/water or coal/oil slurries Densification of fuel/wastes IN-FURNACE CONTROL OPTIONS Combustion control ▪Low excess air ▪Low-NO_x burners	▪Flue-gas recirculation ▪Fuel reburning Advanced low-NO_x burners Furnace sorbent injection Limestone-injection multistage burners Slagging combustors Ammonia-injection process Urea injection process Fluidized-bed combustion Co-combustion of disparate fuels Bottom-ash disposal ▪Landfill ▪Ponding ▪Ocean disposal ▪Mine backfill ▪Reuse processes POST-COMBUSTION CONTROL PROCESSES Wet lime/limestone FGD	Spray-dryer FGD Recovery FGD processes ▪Gypsum ▪Sulfur/sulfuric acid Selective catalytic reduction ▪Hot-side ▪Cold-side Combined SO_2/NO_x processes Fabric filters Mechanical collectors Electrostatic precipitators ▪Hot-side ▪Cold side Wet particulate scrubbers E-SO_xSO_2/flyash process Electron-beam processes Sodium-sorbent injection Calcium-sorbent injection Flyash disposal ▪Stabilization ▪Ponding ▪Reuse processes	Sludge disposal ▪Stabilization ▪Ponding/land filling ▪Wet stacking of gypsum AUX-EQUIPMENT TIE-INS FGD reheaters ▪Gas/gas exchangers ▪Gas/liquid/gas exchangers ▪Indirect hot air ▪Direct combustion ▪In-line reheat ▪Flue-gas bypass Stack ▪Wet-stack operation ▪Conventional stack Cooling towers ▪Natural draft ▪Mechanical draft Once-through cooling Cooling ponds Air-cooled surface condensers FGD exhaust discharge through cooling tower

burners. A distributed mixing concept is illustrated in Fig. 1.12 while a distributed mixing burner is shown in Fig. 1.13. It is interesting to note that the tangentially-fired furnaces have inherently lower NO_x emissions than the wall-fired and the cyclone furnaces.

The fly-ash particulates may be removed in mechanical collectors, fabric filters, wet scrubbers, or electrostatic precipitators (ESP). The fabric filters and the electrostatic precipitators are the leading technologies, the electrostatic precipitator being the most commonly used today. In the electrostatic precipitator, the fly-ash particulates from flue gas are electrically charged, driven to collecting electrode plates by an electrical field, and then removed and disposed of. An electrostatic precipitator is illustrated in Fig. 1.14.

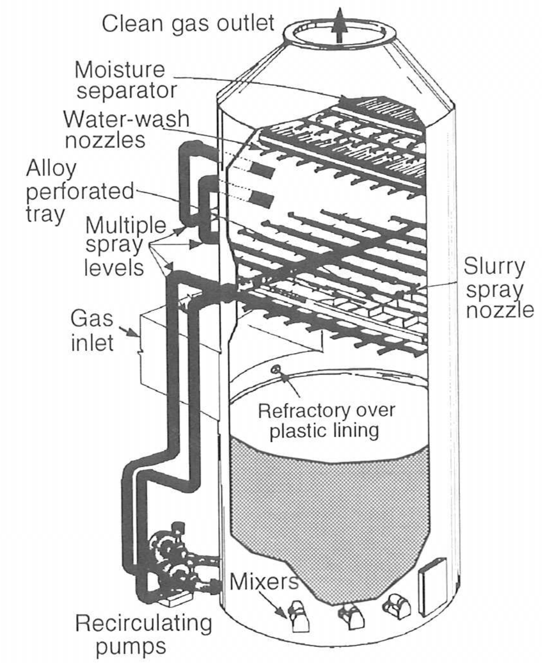

Fig. 1.11 Spray tower absorber (published with permission from ref. 40).

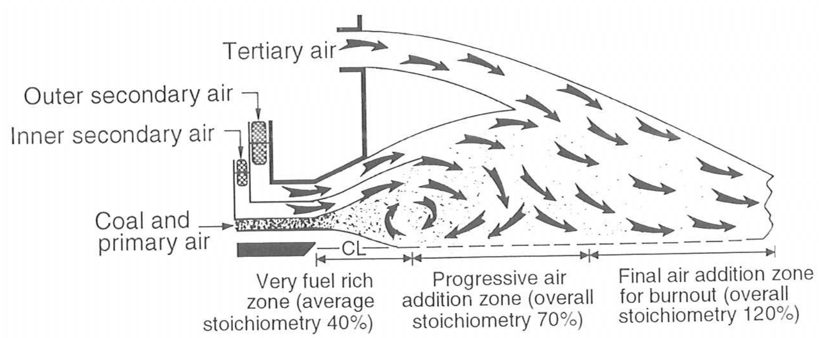

Fig. 1.12 Distributed mixing burner concept (published with permission from ref. 36).

(iii) *Developments*. Many new pulverized coal combustion technologies are being developed. Most are classified as the clean coal technologies, concerned with controlling and reducing pollution. Some of these technologies being developed in Europe were listed in Tables 1.8 and 1.9. The pulverized coal combustion technologies being developed and demonstrated in the United States under the Clean Coal Technologies Demonstration Program were presented in Table 1.11.

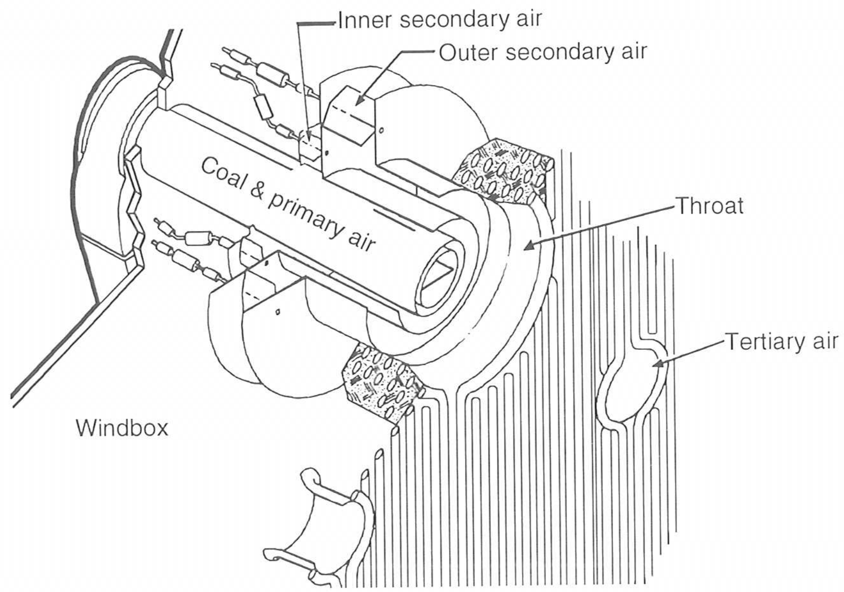

Fig. 1.13 Distributed mixing burner (published with permission from ref. 36).

A demonstration project at the Ohio Edison's Edgewater Station, Fig. 1.15, is described in more detail as being representative for these developments (ref. 31). The project objective is to demonstrate, with a variety of coals and sorbents, a limestone injection multistage burner (LIMB) process for simultaneous control of SO_x and NO_x. The process is expected to achieve up to 60% NO_x and 60% SO_x reduction. In the process, the dry limestone sorbent is injected into the furnace at a point above the low-NO_x burners. The burners reduce NO_x formation by staging combustion. The sorbent travels through the boiler and is removed along with the fly-ash in the existing electrostatic precipitator. Humidification of the flue gas before it enters the ESP is necessary to maintain normal operation and to enhance SO_2 removal. In addition, using the duct injection of the dry lime sorbent upstream of the humidifier and the precipitator, up to 80% SO_x reduction is expected. A chemical additive is added in the humidification water to improve SO_2 absorption. The project is conducted on a commercial, wall-fired, 105 MWe boiler.

A summary of the technical issues associated with some of the clean coal technologies is provided in Table 1.14. Additional discussion of NO_x/SO_x control in boilers is given in Chapter 6.

A clean coal technology of considerable potential interest is coal slurry technology. Interest in the use of coal slurries, and particularly coal-water mixtures

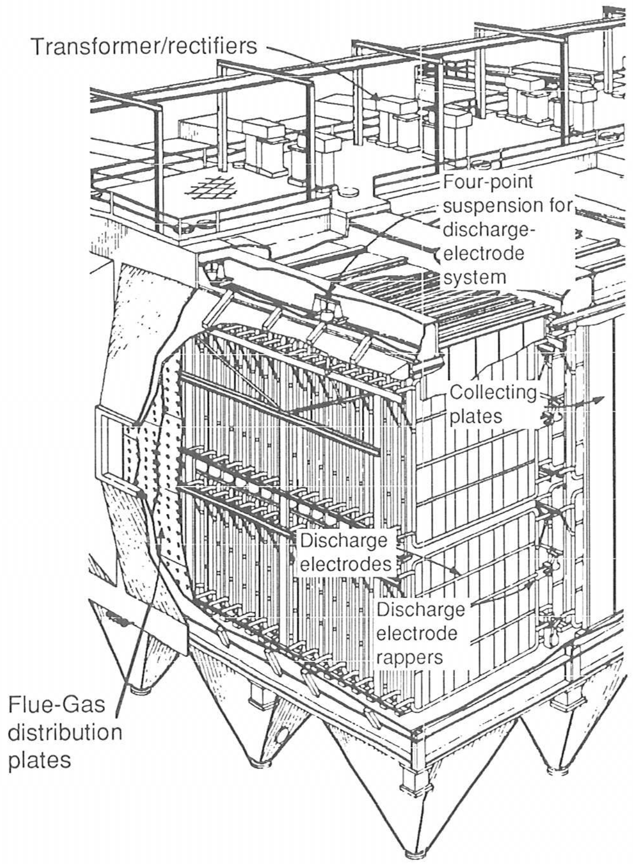

Fig. 1.14 Electrostatic precipitator (published with permission from ref. 41).

(CWM), centers largely around use of coal slurries as a replacement fuel for existing oil-fired boilers. In addition, CWM may also be useful in ignition of pulverized coal in existing furnace systems, and as a substitute fuel in gas turbines. Research results for coal-oil mixtures (COM) have shown little economic incentive for COM as an oil replacement fuel. Further, full-scale utility boiler test results have uncovered unexpected problems in handling of ash fouling with the use of coal-oil slurries.

Efforts to develop coal-water mixtures are much more recent and early test results have been encouraging. deLesdernier *et al.* (ref. 43) show for a specific 200-MWe oil-fired boiler that CWM may have some economic incentive. They note that the critical technical issues include development and integration of advanced coal cleaning methods for up-front reduction of sulfur and ash levels and demonstration of high combustion efficiency, reliability, and performance in a utility boiler. An extensive recent review of the coal slurry technologies is provided by Papachristodoulou and Trass (ref. 44).

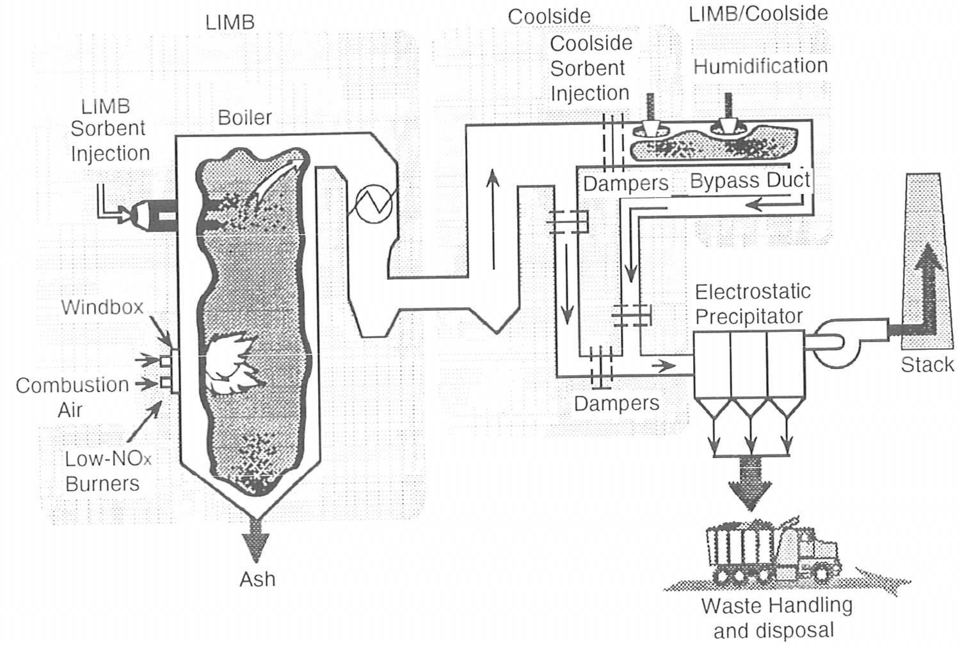

Fig. 1.15 LIMB demonstration project (published with permission from ref. 31).

1.2.2 Gasification

(i) *Processes*. Coal gasification is becoming increasingly important particularly in conjunction with integrated gasification combined cycle, IGCC. Physical and chemical processes in coal gasification are similar to processes in coal combustion. One of the main processes is still coal combustion, *i.e.*, exothermic, heterogeneous reaction of carbon from coal with oxygen from air to produce carbon dioxide and carbon monoxide as shown in eqns. 1.1 and 1.2. In coal gasification, however, only a part of the oxygen needed for stoichiometric combustion, typically around 20 percent (ref. 28), is provided and thus only a part of the available carbon is consumed by combustion. The remaining carbon is consumed in gasification reactions with carbon dioxide, steam, and hydrogen. The heterogeneous reactions of carbon with carbon dioxide and steam,

$$C + CO_2 = 2\,CO \tag{1.3}$$

$$C + H_2O = CO + H_2 \tag{1.4}$$

TABLE 1.14

Technical issues related to SO_x/NO_x control technologies (published with permission from ref. 42)

Commercial Status	Applicability	SO_2 and NO_x Reduction Potential	Critical Issues
Pre-Combustion Control			
Physical Coal Cleaning			
Commercial	Most economically applied to coals > 1% S	10 to 30% SO_2 reduction typical up to 60% SO_2 reduction on easy-to-clean coals	SO_2 reduction limited by pyritic S content Benefits of cleaning need quantification Potential heat rate penalty due to increased moisture content and fines loss
Coal Switching			
Commercial	Cyclone and wet bottom boilers require low ash fusion temperature coal	SO_2 reduction dependent on sulfur content of original and alternative coals	Potential boiler derating due to fouling, slagging, and moisture content Transportation costs F.O.B. mine costs of low sulfur coal Potential ESP upgrade Potential pulverizer and coal handling equipment upgrade
Combustion Control			
NO_x Combustion Control			
Low to moderate controls commercially demonstrated (low excess air, overfire air, burners-out-of-service, biased firing, low-NO_x burners) Advanced low NO_x burners and improved furnace geometries currently nearing commercial status. Retrofit burners will be available for most unit types (except cyclones) by late 1980's	Retrofit options not currently available for cyclone	Low excess air - 0 to 15% Biased firing - 5% Burners-out-of-service - 20 to 25% Overfire air - 15 to 25% Low-NO_x burners 40 to 60%	Several options must be available due to wide variety of boiler designs in operation Retrofit costs and NO_x reductions attainable are highly site-specific

TABLE 1.14 (Continued)

Technical issues related to SO_x/NO_x control technologies (published with permission from ref. 42)

Commercial Status	Applicability	SO_2 and NO_x Reduction Potential	Critical Issues
Furnace Dry Sorbent Injection			
Not commercially available in U.S. Full-scale demonstrations underway in Europe, Canada and the U.S.	Application may be limited by increased boiler solids loading	50% SO_2 removal likely; higher levels possible	Process not fully characterized Potential negative boiler impacts Particulate control upgrading required Potential adverse impact on ash handling and disposal systems
Post-Combustion Control			
Flue Gas NO_x Control			
Commercial in Japan for SCR - one operating system in U.S. on oil	Applicable to all fossil fuel generation furnaces	80% NO_x reduction for SCR 30 to 60% NO_x reduction for thermal De NO_x	Catalyst life (SCR) SO_3 formation (SCR) NH_3 slip and byproducts Heat rate penalty Reliability
Lime & Limestone FGD			
Commercial - over 60,000 MW in operation or under construction in U.S.	Applicable to virtually all coals	>90% SO_2 removal	Retrofit costs typically vary from 1.1 to 1.4 times the cost of new units Impact on plant availability Retrofit may be constrained by space
Spray Dry FGD			
Commercial 18 systems operating or planned (7500 MW)	Applicable to virtually all coals	Up to 90% SO_2 removal achievable on low S coal Up to 90% removal indicated in short term tests on high sulfur coal (3.5%S)	Baghouse or ESP improvements may be required for retrofit Process not suitable for gypsum production

TABLE 1.14 (Continued)

Technical issues related to SO_x/NO_x control technologies (published with permission from ref. 42)

Commercial Status	Applicability	SO_2 and NO_x Reduction Potential	Critical Issues
	Dual Alkali FGD (Lime and Limestone)		
Commercial - three systems operating in U.S.	Not applicable to low sulfur coal (<1.5% S) Not applicable to gypsum production	>90% SO_2 removal	Limestone system difficult to control Same space and plant constraints as lime and limestone FGD
	Recovery of Salable Product FGD		
MgO (1 plant) and Wellman-Lord (2 plants) commercial in U.S.	Applicable to virtually all coals Most applicable to sites where byproduct disposal is constrained	>90% SO_2 removal	Markets for products must be available Processes are relatively complicated and expensive
	Advanced Throwaway FGD		
Horizontal - 4 systems in operation or under construction in U.S. Chiyoda - 2 systems in operation or under construction Saarberg-Holter - 4 systems operating in Germany Co-current - several in Japan	All applicable over wide range of coals and operating conditions Additives may be advantageous in retrofits to offset design deficiencies	>90% SO_2 removal	Issues similar to those for lime and limestone FGD Little U.S. experience for most of these systems
	Post-Furnace Dry Sorbent Injection		
Field tested at 20 MW on low sulfur coal 100 MW unit operating	Potentially applicable to all coals. However, current sorbents may restrict use to Western plants due to cost Pressure hydrated lime is under testing which may broaden applicabillity and removal efficiency	70-80% SO_2 removal on low S coal	Sorbent availability and cost Spent sorbent disposal - potential leaching of soluble sodium compounds

Note: Table 1.14 indicates some of the critical technical issues though the information on cost and technical status is not current.

are endothermic and produce carbon monoxide and hydrogen. The heterogeneous reaction of carbon with hydrogen,

$$C + 2\,H_2 = C\,H_4 \qquad (1.5)$$

is exothermic and produces methane. Taken together, the gasification reactions are endothermic and must rely on the heat from the exothermic combustion reactions.

In addition to the heterogeneous reactions above, three exothermic, homogeneous reactions, combustion of carbon monoxide and hydrogen and water-gas shift reaction,

$$CO + 1/2\,O_2 = CO_2 \qquad (1.6)$$

$$H_2 + 1/2\,O_2 = H_2O \qquad (1.7)$$

$$CO + H_2O = CO_2 + H_2 \qquad (1.8)$$

are also important.

Devolatilization processes in coal gasification are similar to devolatilization processes in coal combustion. The fate of the devolatilization products, however, depends on the conditions under which they are released. In the entrained bed gasifiers, the devolatilization products are released in the region of high temperature and excess oxygen. Thus, tars, oils, phenols, and hydrocarbon gases are cracked and oxidized to carbon monoxide, hydrogen, carbon dioxide, and steam.

Pollutant formation processes in coal gasification are, however, different from those in coal combustion. The main difference is that under reducing conditions, sulfur from coal is converted mostly to H_2S and small amounts of COS rather than to SO_2. The reduced sulfur species, H_2S and COS, can be removed from the product gas by a variety of commerically available processes. The other difference is that under reducing conditions, almost no NO_x is formed. Nitrogen from coal is converted mostly to NH_3 and small amounts of HCN. However, the use of the product gas as a fuel still leads to NO_x formation.

The main differences between coal combustion and gasification are summarized in Table 1.15. The main characteristics of entrained bed gasification are: high temperature, slagging operation, entrainment of some molten slag in the product gas, high oxidant requirements, large sensible heat in the product gas, and ability to handle all coal ranks regardless of caking characteristics and the amount of fines (ref. 28).

TABLE 1.15

Differences between coal combustion and gasification (published with permission from ref. 26)

	Coal Combustion	Coal Gasification
Operating temperature	Lower	Higher
Operating pressure	Usually atmospheric	Often high pressure
Ash condition	Often dry	Often slagging
Feed gases	Air	Steam and oxygen or air
Product gases	CO_2, H_2O	CO, H_2, CH_4, CO_2, H_2O
Gas cleanup	Post-scrubbing	Intermediate scrubbing
Pollutants	SO_2, NO_x	H_2S, HCN, NH_3
Char reaction rate	Fast (with O_2)	Slow (with CO_2, H_2O)
Oxidizer	In excess	Deficient
Tar production	None	Sometimes
Purpose	High-temperature gas	Fuel-rich gas

(ii) *Technologies.* Entrained bed gasification technologies are still in the state of intensive development. They will be illustrated by describing two commerically proven gasifiers: the Koppers-Totzek gasifier and the Texaco gasifier.

The Koppers-Totzek (or more recently GKT for Gessellshaft fur Kohle-Technologie) gasifier, shown in Fig. 1.16, is an atmospheric pressure, entrained flow gasifier. The feed coal is dried and pulverized to fine powder in a pulverizer. Typically 70 to 80 percent of the pulverized coal particles pass through a 200 mesh sieve of 74 μm apertures. The dry, pulverized coal is fed through screw feeders to two opposing burners. The coal reacts with oxygen and steam producing a temperature of approximately 2,200 K in the flame zone. The temperature of the gas mixture is reduced to approximately 1,760 K by heat losses to the refractory-lined and steam-jacketed walls of the gasifier. At this temperature the coal is converted primarily to CO, H_2, and CO_2 and much of the ash is converted to molten slag. A part of this molten slag flows down the gasifier walls into a quench tank where it solidifies before being removed. Another part leaves the gasifier as fly ash. The product gas leaving the gasifier is water-quenched to approximately 1200 K to solidify entrained molten ash before entering a waste heat boiler. The fly ash is removed after the waste heat boiler by wet scrubbers and electrostatic precipitators. The scrubbed and cooled product gas is then processed in a sulfur removal system resulting in a medium heating value gas. Most of the Koppers-Totzek gaisifers are with two burners-two heads. The two-headed gasifiers have a nominal dry gas capacity of 17,000 m^3/hr at standard conditions. This is equivalent to apporximately 210 t/d of MAF coal. The four-headed gasifiers have four burner heads spaced at 90 degrees. Their nominal dry gas capacity is 35,000 m^3/hr at standard conditions which is equivalent to approximately 430 t/d of MAF coal. The most common application of the Koppers-Totzek gasifiers so far has been in ammonia and methanol production (refs. 28,45).

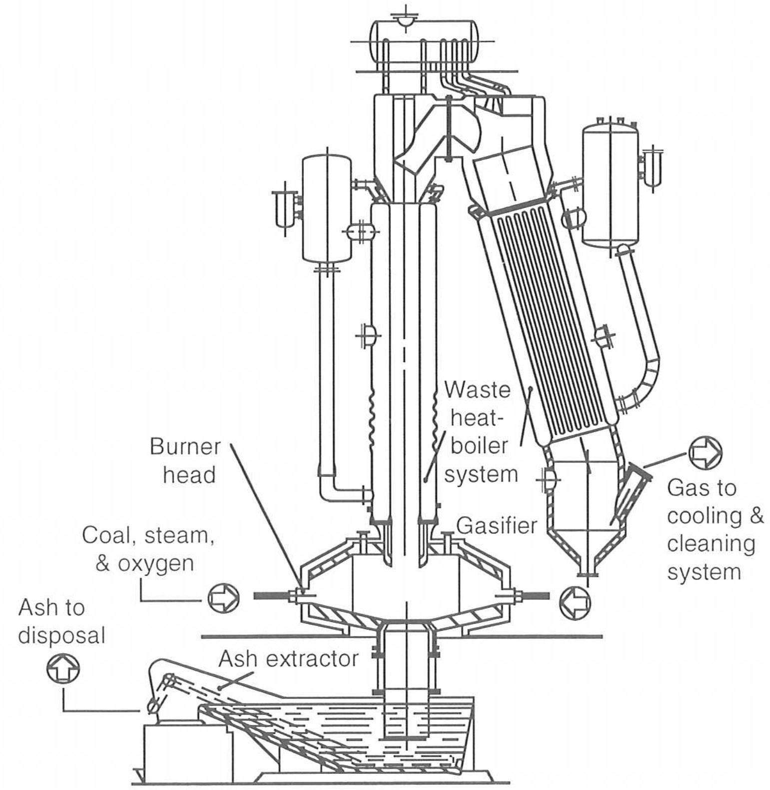

Fig. 1.16 Koppers-Totzek two-headed gasifier (published with permission from ref. 45).

The Texaco gasifier, shown with auxiliary units in Fig. 1.17, is a slurry-fed, pressurized, entrained flow gasifier. The feed coal is pulverized and slurried in a wet rod mill. The slurry water consists of recycled condensate and make-up water. The coal-water slurry, together with oxygen or air, is pumped through a burner into the refractory-lined gasifier from the top. The gasifier pressure is typically around 4 MPa. The coal reacts with oxygen producing high temperatures. The slurry water evaporates and reacts with the coal, moderating temperatures. The gasification takes place at temperatures between 1530 K and 1760 K. At these conditions the coal is converted primarily to CO, H_2, and CO_2 and small amounts of CH_4; no tars or oils are present. Fuel nitrogen is converted to N_2 with some NH_3. Fuel sulfur is reduced to H_2S and small amounts of COS. The ash melts and leaves the gasifier as molten slag. The product gas is either water-quenched or cooled in radiation and convection waste heat boilers before wet scrubbing. The solidified slag, with carbon content of

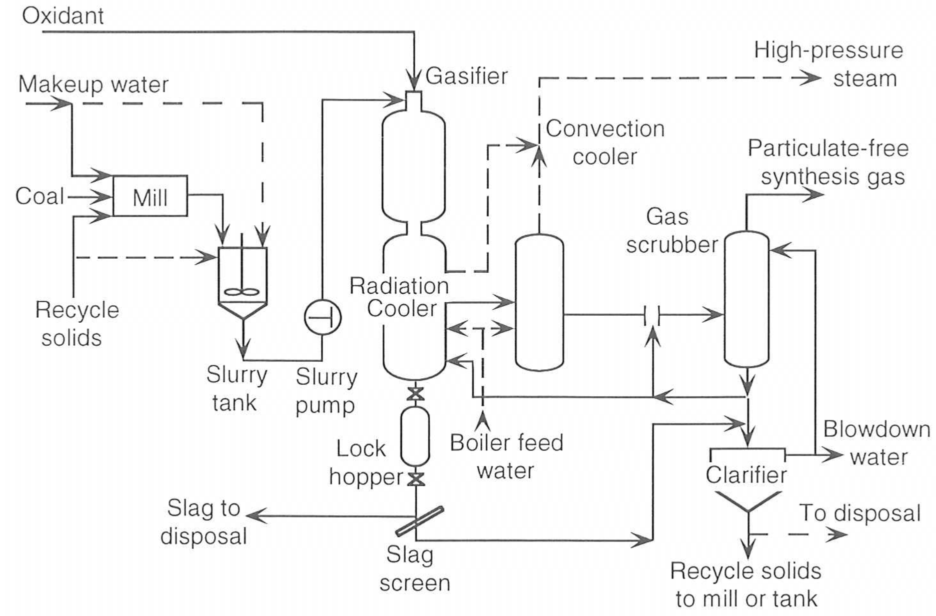

Fig. 1.17 Texaco gasification process (published with permission from ref.28).

less than 1 percent, is removed through a lockhopper for disposal. The product gas of the oxygen-blown Texaco gasifiers has a medium heating value (refs. 28, 45-47).

An important application of the Texaco gasification technology has been in a combined cycle demonstration plant. The 120 MW "Cool Water" plant is an integrated gasification combined cycle power plant located in the Mojave Desert in California. It began power production in 1989. The plant uses an oxygen-blown entrained bed Texaco gasifier to convert approximately 900 tons of coal per day to a medium heating value gas. The product gas is cooled to ambient temperature before removing sulfur species and particulates by conventional methods. The gas, after particulate and sulfur removal, is burned in a gas turbine to produce electricity. Additional electricity is produced in a steam turbine. Steam for the steam turbine is generated from the hot product gas in the waste heat boilers and from the gas turbine exhaust gas in the heat recovery steam generator (HRSG). The emission of SO_2, NO_x, and particulates is only one tenth of the United States New Source Performance Standards (NSPS) for coal-fired plants (refs. 46,47).

(iii) *Developments*. Entrained bed gasification technologies have been or are being developed in the United States, Europe, Japan and other countries. The important technologies in various phases of demonstration or development include: Bituminous Coal Research (BI-GAS); Chevron Research; Combustion Engineering; Destec Energy; Dow Chemical; Krupp-Koppers (Koppers-Totzek), Germany; Mountain Fuels Resources/Eyring Research (MFR/Eyring); Saarbergwerke (Saarberg-Otto), Germany; Shell; and Vereinigte Elelctrizitatswerke Westfaen (VEW), Germany. Some of these technologies being developed in Europe were listed in Table 1.8 and 1.9. The entrained bed gasification technologies being developed and demonstrated under the Clean Coal Technologies Demonstration Program were presented in Table 1.11.

The "Combustion Engineering IGCC Repowering Project" Fig. 1.18, at the City Water, Light, and Power's Lakeside Station in Springfield, Illinois is described in more detail as a representative of these developments (ref. 31). The project objectives are: to demonstrate an advanced, dry-feed, air-blown, two-stage, entrained flow coal gasifier with limestone injection and moving bed, zinc ferrite, hot gas cleanup system; to evaluate a kinetic coal extruder; and to assess reliability, availability, and maintainability at commercial scale.

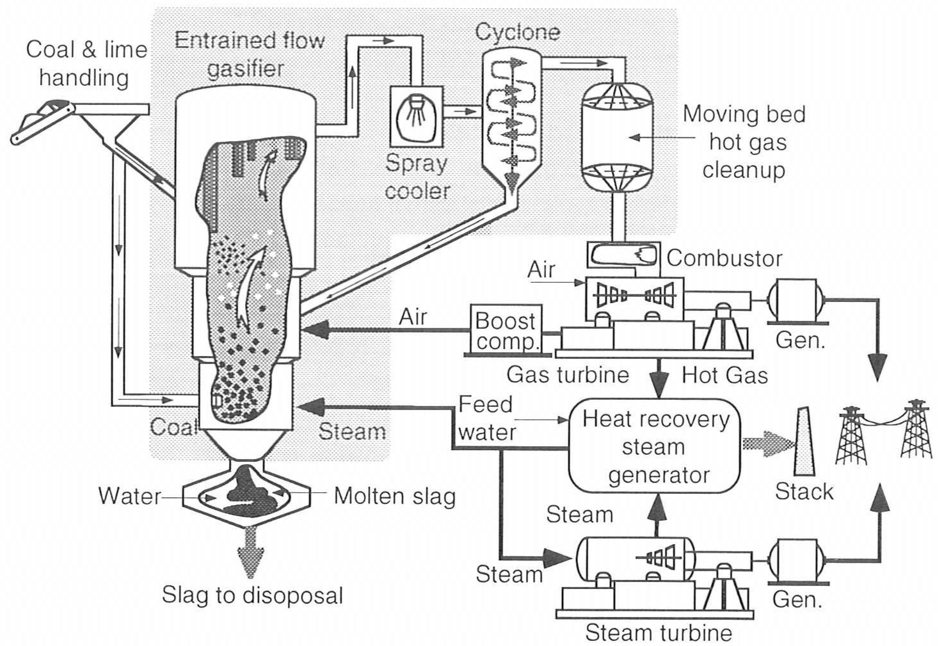

Fig. 1.18 Combustion Engineering IGCC repowering project (published with permission from ref. 31).