GASIFICATION

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Definition

- **Gasification is a process to upgrade a solid feedstock**, which is difficult to handle, by removing undesirable impurities and converting it **into a gaseous form** that can be purified and used directly as a fuel or further reacted to produce other gaseous or liquid fuels, or chemicals.

Reason for Coal Gasification

1. Liquid and gaseous fuels are easier to handle and use than coal, whether the fuel is used for heating, cooking, transportation, or power production.
2. Impurities in coal can be more readily removed through gasification than when utilized directly.
3. Gasification of coal is especially attractive to nations that have coal reserves and lack reserves of oil and gas or are depleting them

Brief History of Coal Gasification

- **In 1609**, a Belgian chemist, **Jan van Helmont**, observed that gas was evolved from coal when it was heated.
- **In 1792**, **William Murdock**, a Scottish engineer, pioneered the commercial gasification of coal using the technique of heating coal in a retort in the absence of air to convert coal to gas and coke.
- The gas produced in this manner (*i.e.*, carbonization) has several names: coal gas, town gas, city gas, or illuminating gas.
- **In 1816**, **the Baltimore Gas Company**, the first coal gasification company in the United States, was established.
- By **the mid-1920s**, about 20% of the gas supply in the United States was being produced from coal.
- **In the 1940s**, the increasing availability of low-cost natural gas led to its substitution for gases derived from coal and the demise of the gasifiers.

Brief History of Coal Gasification

- **In the 1950s and 1960s,** petroleum dominated the market, and no new gasification processes emerged
- **In the late 1960s and early 1970s**, when the United States began to experience natural gas shortages and the oil embargo of the 1970s occurred, that the significance of coal reserves was recognized. This recognition led to a tremendous surge in interest in coal utilization, primarily in the areas of gasification and liquefaction

Principles of Coal Gasification

- Carbonization of coal to produce coal gas is a relatively simple process to perform and is done in a retort in the absence of air.
- The composition of the gas being produced varies depending on the coal being used but is typically comprised of hydrogen (40–50%) and methane (30–40%), with minor amounts (2–10%) of nitrogen, carbon monoxide, ethylene, and carbon dioxide.
- The gas yield is approximately 10,000 scf per short ton of coal carbonized with a heating value of 550 to 700 Btu/scf. When carbonizing a bituminous coal, about 20% of the weight of the coal is converted to gas. This gas is used as a fuel at coking operations.

Principles of Coal Gasification

- Although carbonization of coal is a simple process, only a small fraction of the coal is converted to gas; consequently, processes to convert all of the carbon in the coal to gas were developed.
- In one of these processes, **air is slowly passed through a hot bed of coal, converting most of the carbon to carbon monoxide, with some carbon dioxide being formed**.
- **Some of the carbon dioxide is then converted to carbon monoxide by reacting with hot fuel carbon**.

Principles of Coal Gasification

The reactions that occur are:

- **$C + O_2 \rightarrow CO_2$**

  (Combustion of carbon: ΔH = +170. 0 × 103 Btu/lb mole of carbon gasified)

  and

- **$C + CO_2 \rightarrow 2CO$**

  (Boudouard reaction: ΔH = −72. 19 × 103 Btu/lb mole of carbon gasified)

  resulting in:

- **$2C + O_2 \rightarrow 2CO$**

  (ΔH = +97. 81 × 103 Btu/lb mole of carbon gasified)

Principles of Coal Gasification

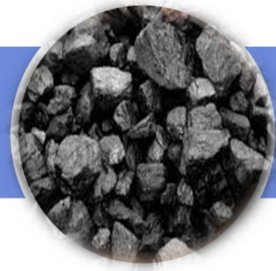
- The gas produced by this method is called **producer gas**, and when a **bituminous coal** is used **the gas composition** is typically **20 to 25% carbon monoxide, 55 to 60% nitrogen, 2 to 8% carbon dioxide, and 3 to 5% hydrocarbons**.
- Unfortunately, the producer gas is diluted with nitrogen, and **the heating value of the gas** is only about **100 to 150 Btu/scf**.
- **The yield of producer gas** is **150,000 to 170,000 scf per short ton of coal**.
- **Producer gas was used in a variety of industrial applications** such as open-hearth furnaces in steel mills, glass-making furnaces, and pottery kilns.

Principles of Coal Gasification

- The temperatures developed in the fuel bed during reactions can be very high, and, when the ash in the bed is fusible, the endothermic carbon–steam reaction must be imposed by adding steam to the air:
- **$C + H_2O \rightarrow CO + H_2$**

  (Carbon–steam reaction: $\Delta H = -58.35 \times 103$ Btu/lb mole of carbon gasified)
- This reaction moderates the temperature and yields hydrogen in the product gas.
- This mixture of carbon monoxide and hydrogen is also called **water gas**.

Principles of Coal Gasification



- A typical **water gas** contains **50% hydrogen, 40% carbon monoxide, and small amounts of carbon dioxide and nitrogen** and has a **heating value of 300 Btu/scf**.
- When a water-gas generator is being blown with air to reheat the bed, producer gas is made from the reaction of the hot carbon with oxygen, **yielding about 35,000 scf of water gas and 80,000 scf of producer gas from one short ton of coal**.
- **Water gas is a useful starting material** for synthesizing chemicals or liquid fuels and is a good source of hydrogen.

Principles of Coal Gasification

- Treating the water gas with steam oxidizes the carbon monoxide to carbon dioxide and increases the amount of hydrogen by the equation:
- **$CO + H_2O \rightarrow CO_2 + H_2$**

  (Water-gas shift reaction: ΔH = +3. 83 × 103 Btu/lb mole of carbon gasified)
- The carbon dioxide can be removed from the product stream, leaving reasonably pure hydrogen.

Principles of Coal Gasification

- Hydrogen can also be reacted with carbon at elevated pressures by the carbon hydrogenation or hydrogasification reaction:
- **$C + 2H_2 \rightarrow CH_4$**

  (ΔH = +39. 38 × 103 Btu/lb mole of carbon gasified)
- and whenever the carbon source generates volatile matter, further quantities of methane will form by thermal cracking.

Gasifier Types

Gasifier Types

- Gasification processes are classified on the basis of **the method used to bring the coal into contact with the gasifying medium (air or oxygen).**
- The three principal commercial modes are **fixed-bed**, **fluidized-bed**, and **entrained-flow systems**.

Gasifier Types

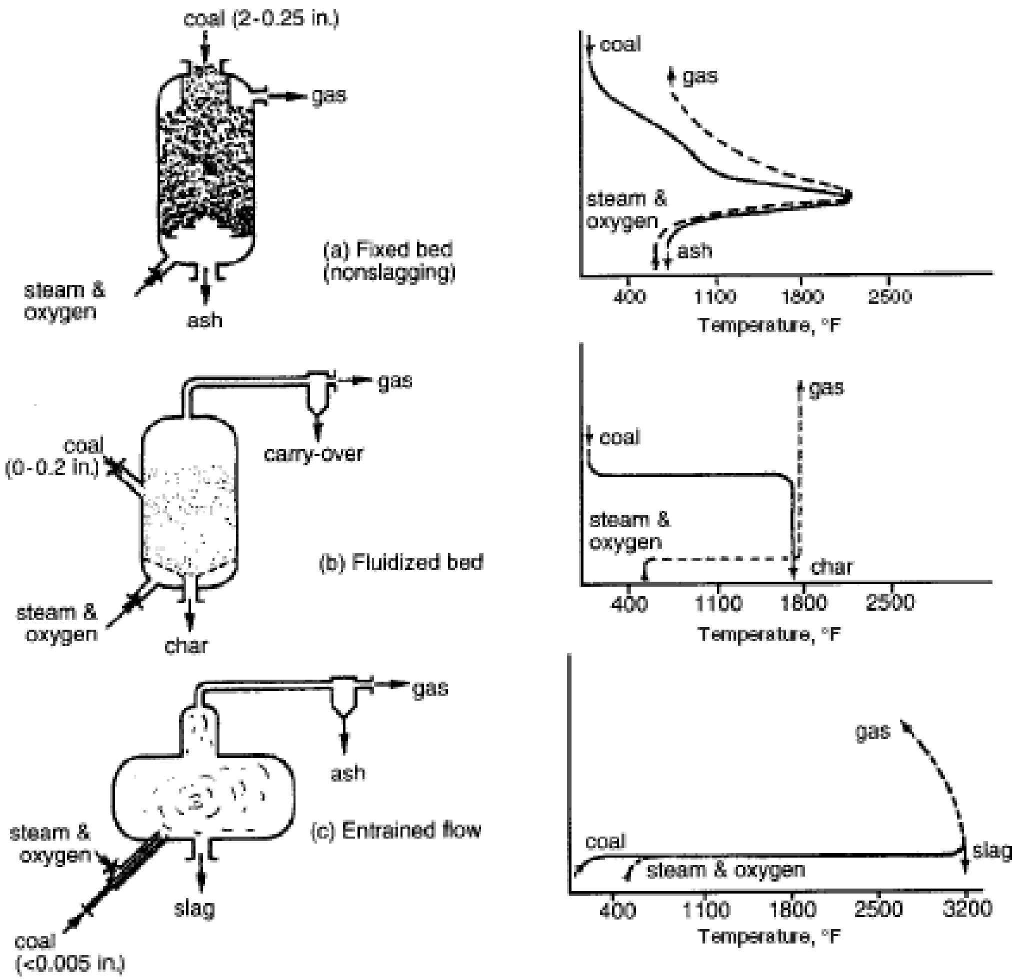


FIGURE 5-22. Classification and characteristics of the commercial gasification systems. (From Elliot, M. A., Ed., *Chemistry of Coal Utilization*, Secondary Suppl. Vol., John Wiley & Sons, New York, 1981. With permission.)

TABLE 5-7
Characteristics of Generic Gasifier Types

	Gasifier Type				
	Fixed Bed		*Fluidized-Bed*		*Entrained Flow*
	Ash Conditions				
	Dry Ash	*Slagging*	*Dry Ash*	*Agglomerating*	*Slagging*
Fuel characteristics					
Fuel size limits	1/4–2 in.	1/4–2 in.	<1/4 in.	≪1/4 in.	<0.005 in.
Caking coal acceptable?	Yes, with modifications	Yes	Possibly	No, noncaking only	Yes
Preferred feedstock	Lignite, reactive bituminous coal, anthracite, wastes	Bituminous coal, anthracite, petcoke, wastes	Lignite, reactive bituminous coal, anthracite, wastes	Lignite, bituminous coal, anthracite, cokes, biomass, wastes	Lignite, reactive bituminous coal, anthracite, petcokes
Ash content limits	No limitation	<25% preferred	No limitation	No limitation	<25% preferred
Preferred ash melting temperature (°F)	>2200	<2370	>2000	>2000	<2372
Operating characteristics					
Exit gas temperature (°F)	Low[a] (800–1200)	Low (800–1200)	Moderate (1700–1900)	Moderate (1700–1900)	High (>2300)
Gasification pressure (psig)	435+	435+	15	15–435	<725
Oxidant requirement	Low	Low	Moderate	Moderate	High
Steam requirement	High	Low	Moderate	Moderate	Low
Unit capacities (MW_{th} equiv.)	10–350	10–350	100–700	20–150	Up to 700
Key distinguishing characteristics	Hydrocarbon liquids in raw gas	Large char recycle			Large amount of sensible heat energy in the hot raw gas
Key technical issue	Utilization of fines and hydrocarbon liquids	Carbon conversion			Raw gas cooling

[a]Fixed-bed gasifiers operating on low-rank coals have exit temperatures lower than 800°F.

Source: Ratafia-Brown, J. *et al.*, *Major Environmental Aspects of Gasification-Based Power Generation Technologies*, Office of Fossil Energy, U.S. Department of Energy, Washington, D.C., December 2002.

Fixed-Bed Gasifier

- In a fixed-bed gasifier, **1/4- to 2-in. coal** is supplied **countercurrent to the gasifying medium**.
- Coal moves slowly down (sometimes this type of gasifier is called a moving-bed gasifier), ideally in plug flow against an ascending stream of gasifying medium.
- Reaction zones, shown in Figure 5-23, typically consist of drying and devolatilization, reduction, combustion, and ash zones.
- In **the drying and devolatilization zone**, located at the top of the gasifier, the entering coal is heated and dried and devolatilization occurs.

Fixed-Bed Gasifier

- In **the reduction/ gasification zone**, the devolatilized coal is gasified by reactions with steam and carbon dioxide.
- In **the combustion zone**, oxygen reacts with the remaining char, and this zone is characteristic of high temperatures.
- The ash is removed from the **bottom of the gasifier** either in dry form if the temperature in the gasifier is controlled with excess steam to maintain the temperature below the ash fusion point or as liquid slag.
- Both the ash and the product gas leave at modest temperature as a result of heat exchange with the entering gasifying medium and fuel, respectively.

Fixed-Bed Gasifier

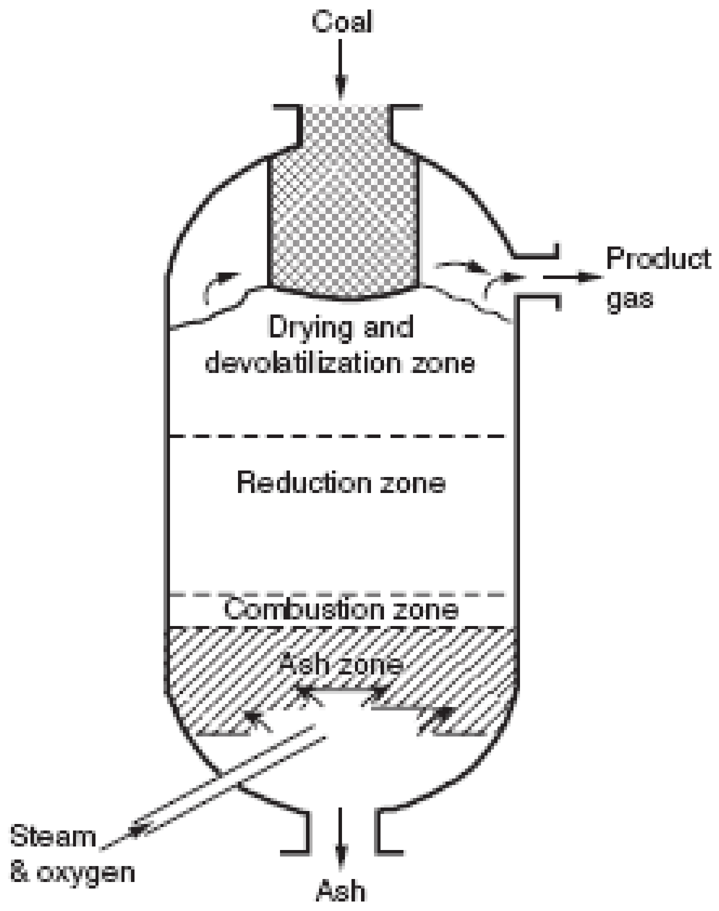


FIGURE 5-23. Reaction zones in a fixed-bed gasifier. (From Elliot, M. A., Editor, *Chemistry of Coal Utilization*, Secondary Suppl. Vol., John Wiley & Sons, New York, 1981. With permission.)

Fixed-Bed Gasifier

Fixed-bed gasifiers have the following characteristics:

1. Low oxidant requirements;
2. Design modifications required for handling caking coal;
3. High cold-gas thermal efficiency when the heating value of the hydrocarbon liquids is included;
4. Limited ability to handle fines.

Fluidized-Bed Gasifier

- In a fluidized-bed gasifier, **coal** crushed to less than **1/8 to 1/4 in**. in size enters the side of the reactor and is kept **suspended by the gasifying medium**.
- Mixing and heat transfer are rapid, resulting in uniform composition and temperature throughout the bed.
- The temperature is sustained below the ash fusion temperature, which avoids clinker formation and possible slumping (*defluidization of the bed).*
- Some char particles are entrained in the product gas as it leaves the gasifier, but they are recovered and recycled back into the gasifier via a cyclone.
- The ash is discharged with the char, and the product gas and char temperatures are high, with some heat transfer occurring with the incoming steam and recycled gas.

Fluidized-Bed Gasifier

Fluidized-bed gasifiers have the following characteristics :

1. Acceptance of a wide range of solid feedstock (including solid waste, wood, and high ash content coals);
2. Uniform temperature;
3. Moderate oxygen and steam requirements;
4. Extensive char recycling.

Entrained-Flow Gasifier

- In the entrained-flow gasifier, **pulverized coal (<0.005 in.)** is entrained with the gasifying medium to react in **co-current flow** in a **high-temperature flame**.
- Residence time in this type of gasifier is very short.
- Entrained-flow gasifiers generally use oxygen as the oxidant and operate at high temperatures, well above ash-slagging conditions, to ensure high carbon conversion.
- The ash exits the system as a slag. The product gas and slag exit close to the reaction temperature

Entrained-Flow Gasifier

Entrained-flow gasifiers have the following characteristics:

1. Ability to gasify all coals regardless of coal rank, caking characteristics, or amount of coal fines, although feedstocks with lower ash contents are favored;
2. Uniform temperatures;
3. Very short fuel residence times in the gasifier;
4. Very finely sized and homogenous solid fuel required;
5. Relatively large oxidant requirements;
6. Large amount of sensible heat in the raw gas;
7. High-temperature slagging operation;
8. Entrainment of some molten slag in the raw gas.

Influence of Coal Properties on Gasification

Moisture

- **Fixed-bed gasifiers** can accommodate moisture contents of **up to 35%**, provided the ash content is not in excess of about 10%.
- Predrying may be performed if the moisture and ash contents are above these amounts.
- **Entrained-flow or fluidized-bed gasifiers** require the moisture content to be reduced to **less than ~5%** by drying to improve coal handling.
- In the entrained-flow system, the residual moisture contributes to the gasification steam but requires heat to evaporate it.

Ash

- Ash should be kept at a minimum because provisions must be made for introducing it to and withdrawing it from the system, provisions that add to the complexity and cost of the overall system.
- In **fixed-bed systems**, ash **accumulates at the base of the fuel bed** and is withdrawn by a mechanical grate if unfused or through a taphole if it is a liquid slag.
- In **the entrained-flow system**, it is removed as a **liquid slag**.
- In **fluidized-bed systems**, the ash is **mixed with the char** and the ash is separated either by sintering and agglomeration of the ash or circulation from the bed through a fully-entrained combustor to melt and separate the ash as a liquid slag.
- Fluidized-bed and entrained-flow gasifiers tend to have higher losses of carbon in the ash than the fixed-bed systems.

Volatile Matter

- The volatile matter from the coal can add to the products of gasification without incurring steam decomposition or oxygen consumption.
- **The volatile matter**, which can vary from **less than 5%** (on a moist, ash-free basis) for anthracite to **over 50%** for subbituminous coal or lignites, can consist of carbon oxides, hydrogen, and traces of nitrogen compounds.
- The volatile matter composition, the type of coal, and the conditions under which the volatile matter is driven off affect the nature of the residual fixed carbon or char that remains.

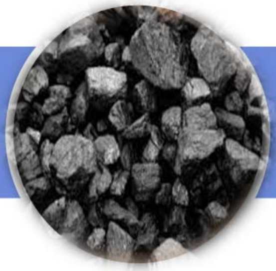
Fixed Carbon

- The nature of the **fixed carbon**, which is the major component of the char after the moisture and volatile matter are driven off, is **important to the performance of the gasifier** and can vary physically and chemically.
- Properties such as density, structure, friability/strength, and reactivity depend primarily on the original coal but they are influenced by the pressure, rate at which the coal is heated, and its final temperature

Caking Tendencies

- The **caking tendencies** of the coal—strongly caking and swelling, weakly caking, and noncaking—must be **considered in the gasifier and process design**.
- Some gasifiers can be designed to handle caking and swelling coals, but others will require the coal to be pretreated.

Ash Fusion



- The **ash fusion temperature** is a measure of when the ash will melt and transform from a solid to a liquid state.
- This temperature is an **important parameter** for the **design and operation of gasification systems**.
- For those that operate below the ash fusion temperature so as not to incur fusion, sintering, or clinkering of the ash, as well as those gasification systems that operate above the ash fusion temperature to promote slag production.
- Another important ash characteristic is the relationship between temperature and ash viscosity as the flow characteristics of the slag are critical.

Reactivity

- Coals vary in their reactivity to steam and to a lesser extent to hydrogen.
- **Reactivity has three important influences**:
  1. it favorably influences methane formation;
  2. it reduces oxygen consumption by allowing steam decomposition down to a lower temperature; and
  3. it allows less steam to be used per volume of oxygen or air than with less reactive coals without incurring ash clinkering.

Coal Size Distribution

- The coal size limits are important gasifier system design considerations.
- In **fixed-bed gasification systems**, **provisions** have to be made for the fines that are generated from mining, transportation, and processing.
- This may include steam and power generation or briquetting, extrusion, or injection to allow them to be supplied to the fixed-bed gasifier.
- The size distribution is **less critical** with **fluidized-bed and entrained-flow gasification systems**.

Commercial Gasification Systems

Commercial Gasification Systems

TABLE 5-8
Largest 30 Commercial Gasification Projects in the World

Gasification Plant Owner	*Location*	*Gasification Technology*	*Output (MW_t equiv.)*	*Startup Year*	*Feed/Product*
Sasol-II	South Africa	Lurgi dry ash	4130	1977	Subbituminous coal/F-T liquids
Sasol-III	South Africa	Lurgi dry ash	4130	1982	Subbituminous coal/F-T liquids
Respol/Iberdrola	Spain	ChevronTexaco	1654	2004	Vacuum residue/electricity
Dakota Gasification Company	United States	Lurgi dry ash	1545	1984	Lignite and refinery residue/SNG
SARLUX srl	Italy	ChevronTexaco	1067	2000	Visbreaker residue/electricity and H_2
Shell MDA Sdn. Bhd.	Malaysia	Shell	1032	1993	Natural gas/mid-distillates
Linde AG	Germany	Shell	984	1997	Visbreaker residue/H_2 and methanol
ISAB Energy	Italy	ChevronTexaco	982	1999	ROSE asphalt/electricity and H_2
Sasol-I	South Africa	Lurgi dry ash	911	1955	Subbituminous coal/F-T liquids
Total France/EdF/ Texaco	France	ChevronTexaco	895	2003	Fuel oil/electricity and H_2
Unspecified owner	United States	ChevronTexaco	656	1979	Natural gas/methanol and CO
Shell Nederland Raffinaderij BV	The Netherlands	Shell	637	1997	Visbreaker residue/H_2 and electricity
SUV/EGT	Czech Republic	Lurgi dry ash	636	1996	Coal/electricity and steam
Chinese Petroleum Corporation	Taiwan	ChevronTexaco	621	1984	Bitumen/H_2 and CO
Hydro Agri Brunsbüttel	Germany	Shell	615	1978	Heavy vacuum residue/ammonia
Public Service of Indiana	United States	E-Gas (Destec)	591	1995	Bituminous coal/electricity
VEBA Chemie AG	Germany	Shell	588	1973	Vacuum residue/ammonia and methanol
Elcogas SA	Spain	Prenflow	588	1997	Coal and petcoke/electricity
Motiva Enterprises LLC	United States	ChevronTexaco	558	1999	Fluid petcoke/electricity and steam
API Raffineria di Anocona S.p.A.	Italy	ChevronTexaco	496	1999	Visbreaker residue/electricity
Chempoetrol a.s.	Czech Republic	Shell	492	1971	Vacuum residue/ammonia and methanol
Demkolec BV	Netherlands	Shell	466	1994	Bituminous coal/electricity
Tampa Electric Company	United States	ChevronTexaco	455	1996	Coal/electricity
Ultrafertil S.A.	Brazil	Shell	451	1979	Asphalt residue/ammonia
Shanghai Pacific Chemical Corp.	China	ChevronTexaco	439	1995	Anthracite/methanol and town gas
Exxon USA, Inc.	United States	ChevronTexaco	436	2000	Petcoke/electricity and syngas
Shanghai Pacific Chemical Corp.	China	IGT U-GAS	410	1994	Bituminous coal/fuel gas and town gas
Gujarat National Fertilizer Co.	India	ChevronTexaco	405	1982	Refinery residue/ammonia and methanol
Esso Singapore Pty. Ltd.	Singapore	ChevronTexaco	364	2000	Residual oil/electricity and H_2
Quimigal Adubos	Portugal	Shell	328	1984	Vacuum residue/ammonia

Note: F-T, Fischer–Tropsch synthesis; SNG, synthetic natural gas.

Source: SFA Pacific, Inc., and U.S. DOE, *Gasification: Worldwide Use and Acceptance*, Office of Fossil Energy, U.S. Department of Energy, Washington, D.C., January 2000.

Commercial Gasification Systems

Fixed-Bed Gasifiers

Lurgi Gasifier

- The most successful fixed-bed gasifier is the Lurgi gasifier, which was developed in Germany during the 1930s as a means to produce town gas.
- The first commercial plant was built in 1936.
- It was initially used for lignites, but process developments in the 1950s allowed for the use of bituminous coals as well.
- The Lurgi gasification process has been used extensively worldwide.

Lurgi Gasifier

- The Lurgi dry-ash gasifier, shown schematically in Figure 5-28, is a pressurized gasifier typically operating at 30 to 35 atm.
- Sized coal enters the top of the gasifier through a lock hopper and moves down through the bed.
- Steam and oxygen enter at the bottom and react with the coal as the gases move up the bed.
- Ash is removed at the bottom of the gasifier by a rotating grate and lock hopper and is kept in a dry state through the injection of steam to cool the bed below the ash fusion point.

Lurgi Gasifier

- As the coal moves down the gasifier it goes through sequential stages of drying and devolatilization with the resultant char undergoing gasification and combustion.
- The countercurrent operation results in a temperature drop in the gasifier.
- Gas temperatures are approximately 500 to 1000°F in the drying and devolatilization zone, 1800°F in the gasification zone, and 2000°F in the combustion zone.
- The raw syngas, a mixture of carbon monoxide and hydrogen, which also contains tar, exits the gasifier at 570 to 930°F.

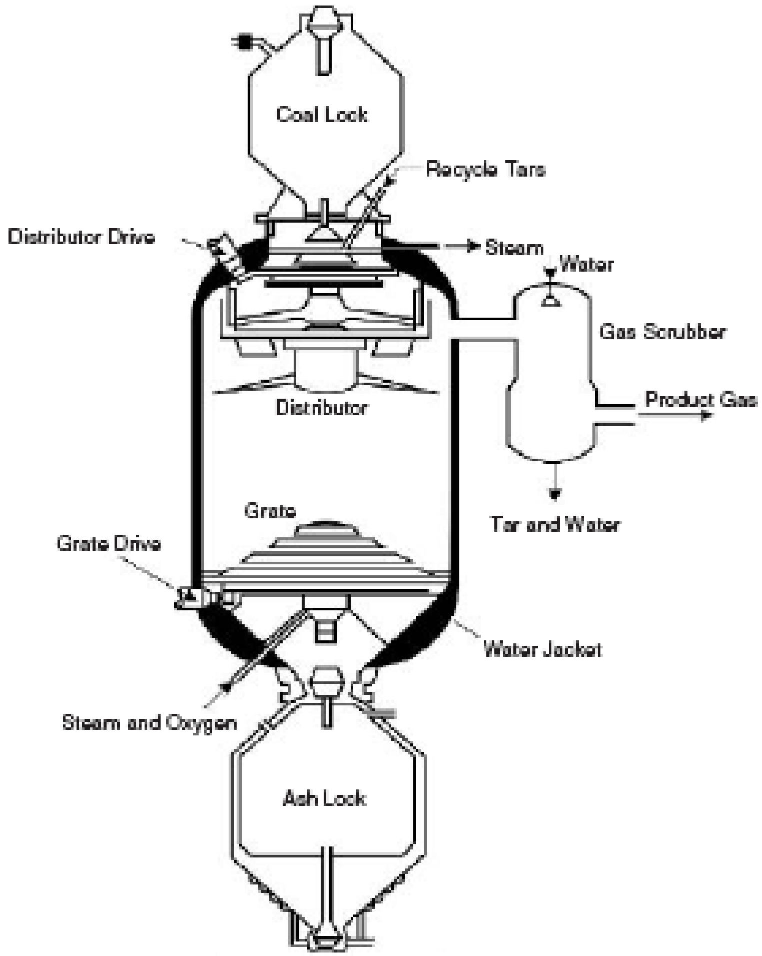


FIGURE 5-28. Schematic diagram of a modern Lurgi dry-ash gasifier. (From Berkowitz, N., *An Introduction to Coal Technology*, Academic Press, New York, 1979. With permission.)

BGL Gasifier

- The BGL (The British Gas and Lurgi) fixed-bed gasifier was developed in the 1970s to provide a syngas with a high methane content in order to provide an efficient means of manufacturing SNG from coal.
- The BGL fixed-bed gasifier, shown schematically in Figure 5-29, is a dry-feed, pressurized, slagging gasifier.
- The operational concept is similar to the Lurgi dry-ash gasifier with two notable differences.
- The BGL fixed-bed gasifier is more fuel flexible in that it can use run-of-mine coal (rather than sized coal), and the gasifier is operated at temperatures above the ash fusion point to form a liquid slag.

BGL Gasifier

- Slag is withdrawn from the slag pool through an opening in the grate.
- The slag flows into a quench chamber and lock hopper in series.
- Syngas exits the gasifier at ∼1040°F and passes into a water quench vessel and a boiler feedwater preheater designed to lower the gas temperature to approximately 300°F.
- Soluble hydrocarbons, such as tars, oils, and naphtha, are recovered from the aqueous liquor in a gas–liquor separation unit and recycled to the gasifier.

BGL Gasifier

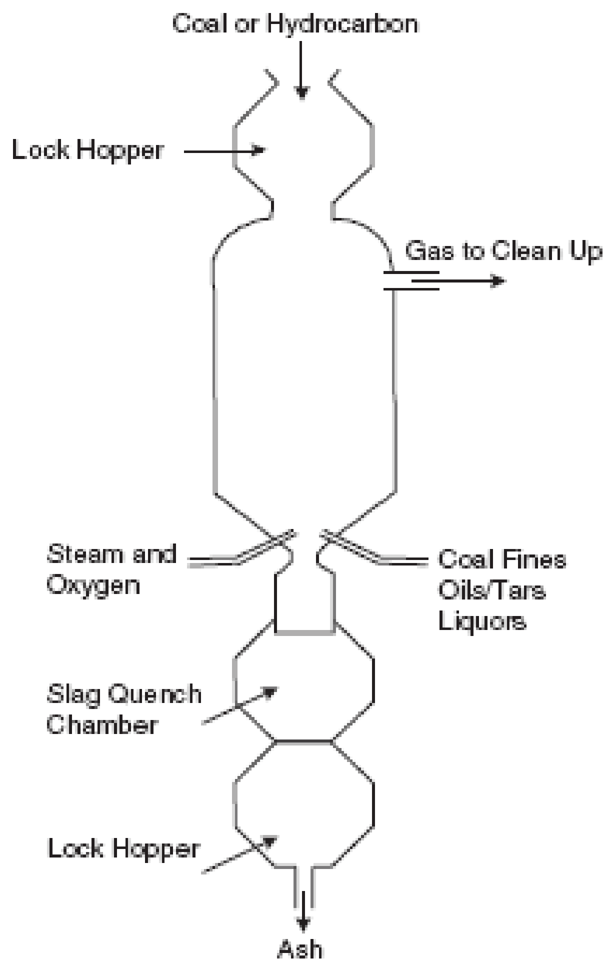


FIGURE 5-29. Schematic diagram of the BGL fixed-bed gasifier. (Adapted from Ratafia-Brown, J. *et al.* [44].)

Commercial Gasification Systems

Fluidized-Bed Gasifiers

HTW Gasifier

- The high-temperature Winkler (HTW) gasifier, shown schematically in Figure 5-30, is a dry-feed, pressurized, fluidized-bed, dry-ash gasifier.
- The HTW process was developed by Rheinbraun in Germany during the 1920s to utilize coal with a small particle size and too friable for use in existing fixed-bed gasifiers.
- The HTW technology is capable of gasifying a variety of feedstocks, including reactive low-rank coals with a higher ash-softening temperature and reactive caking and noncaking bituminous coals.

HTW Gasifier

- Coal with a particle size less 1/8 in. is fed into the gasifier using a screw feeder.
- The upward flow of the gasifying medium, air or oxygen, keeps the particles of coal, ash, and semi-coke/char in a fluidized state.
- Gas and elutriated solids flow up the gasifier, and additional air or oxygen is added in this region to complete the gasification reactions.
- Fine ash particles and char that are entrained in the gas are removed in a cyclone and recycled to the gasifier.
- Ash is removed from the base of the gasifier by means of an ash screw.

HTW Gasifier

- The syngas exiting the gasifier is at a high temperature so it does not contain any high-molecular-weight hydrocarbons such as tars, phenols, and other substituted aromatic compounds.
- The gasifier fluid bed is operated at about 1470 to 1650°F, and the temperature is controlled to ensure that it does not exceed the ash-softening point.
- The temperature in the freeboard can be significantly higher, up to 2000°F.
- The operating pressure can vary between 145 psig for syngas manufacture and 360 to 435 psig for an IGCC application.

HTW Gasifier

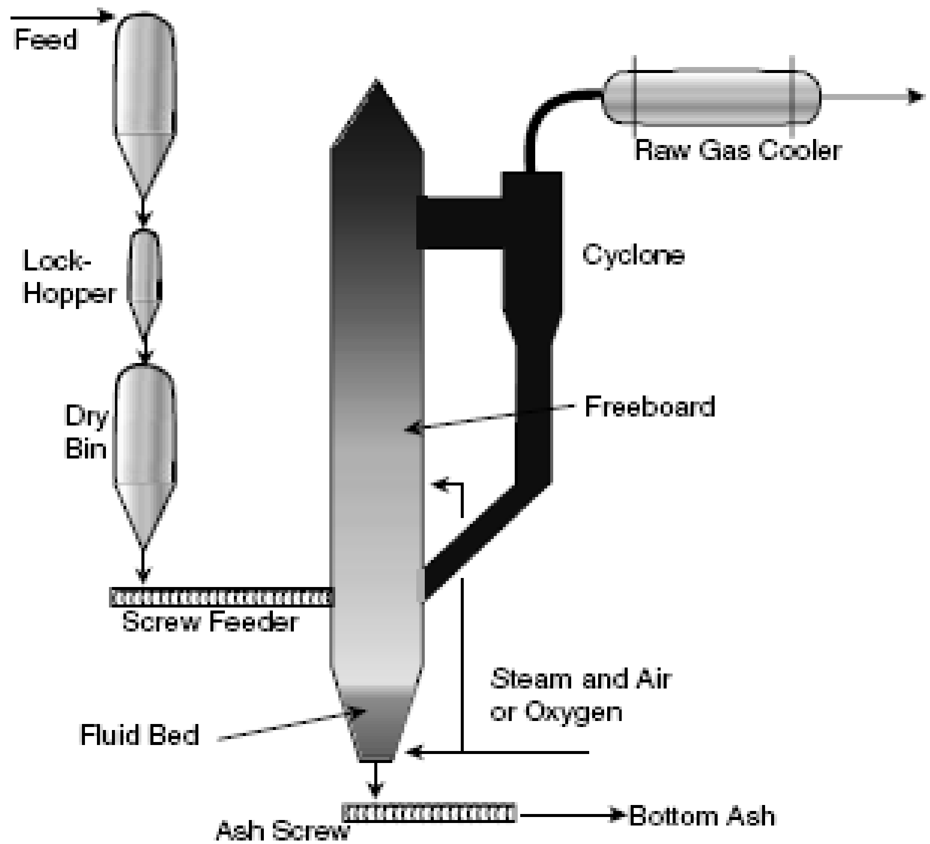


FIGURE 5-30. Schematic diagram of an HTW fluidized-bed gasifier. (From Ratafia-Brown, J. *et al.*, *Major Environmental Aspects of Gasification-Based Power Generation Technologies*, Office of Fossil Energy, U.S. Department of Energy, Washington, D.C., December 2002.)

KRW Gasifier

- The Kellogg–Rust–Westinghouse gasifier, shown schematically in Figure 5-31, is a pressurized, dry feed, fluidized-bed, slagging gasifier developed by the M.W. Kellogg Company.
- The KRW gasifier is capable of gasifying all types of coals, including high-sulfur, high-ash, low-rank, and high-swelling coals.
- Coal and limestone, crushed to less than 1/4 in., are fed into the bottom of the gasifier, and air or oxygen enters through concentric, high-velocity jets.
- This process ensures thorough mixing of the fuel and air or oxygen.

KRW Gasifier

- The coal immediately releases its volatile matter upon entering the gasifier, and it oxidizes rapidly to produce the heat for the gasification reactions.
- An internal recirculation zone is established, with the coal/char moving down the sides of the gasifier and back into the central jet.
- Steam that is introduced with the air or oxygen and through jets in the side of the gasifier reacts with the char to form the syngas.
- Fine ash particles that are carried out of the bed are captured in a high-efficiency cyclone and reinjected into the gasifier.

KRW Gasifier

- The internal recycling of the larger char particles results in the char becoming enriched in ash, and the low-melting components of the ash cause the ash particles to agglomerate.
- As the ash particles become larger, they begin to migrate toward the bottom of the gasifier where they are removed along with spent sorbent (i.e., limestone that has reacted with sulfur to form calcium sulfide (CaS)) and some unreacted char.
- The ash, char, and spent sorbent flow into a fluidized-bed sulfator, where the char and calcium sulfide are oxidized.
- The calcium sulfide forms calcium sulfate, $CaSO_4$, which is chemically stable and can be disposed of in a landfill.

KRW Gasifier

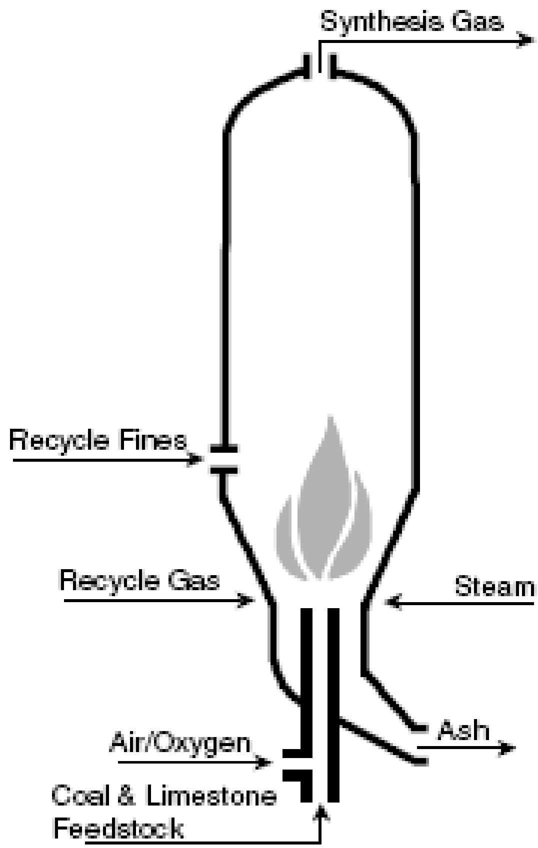


FIGURE 5-31. Schematic diagram of the KRW gasifier. (From Ratafia-Brown, J. *et al.*, *Major Environmental Aspects of Gasification-Based Power Generation Technologies*, Office of Fossil Energy, U.S. Department of Energy, Washington, D.C., December 2002.)

Commercial Gasification Systems

Entrained-Flow Gasifiers

Chevron Texaco Gasifier

- The ChevronTexaco gasifier, shown schematically in Figure 5-32, is a single-stage, down-fired, entrained-flow gasifier.
- A fuel–water slurry (e.g., 60–70% coal) and 95% pure oxygen are fed to the pressurized gasifier. The coal and oxygen react exothermally at a temperature ranging from 2200 to 2700°F and a pressure greater than 20 atm to produce syngas and molten ash.
- Operation at the high pressures eliminates the production of hydrocarbon gases and liquids in the syngas.

Chevron Texaco Gasifier

- The hot gases are cooled using either a radiant syngas cooler located inside the gasifier to produce high pressure steam or an exit gas quench.
- Slag drops into the water pool at the bottom of the gasifier, is quenched and separated from the blackwater, and is removed through a lockhopper.
- The ChevronTexaco technology has operated commercially for over 40 years with feedstocks such as natural gas, heavy oil, coal, and petroleum coke.
- Currently, 60 commercial plants are in operation, with 12 using coke and coal, 28 using oil, and 20 using a gas feedstock.

Chevron Texaco Gasifier

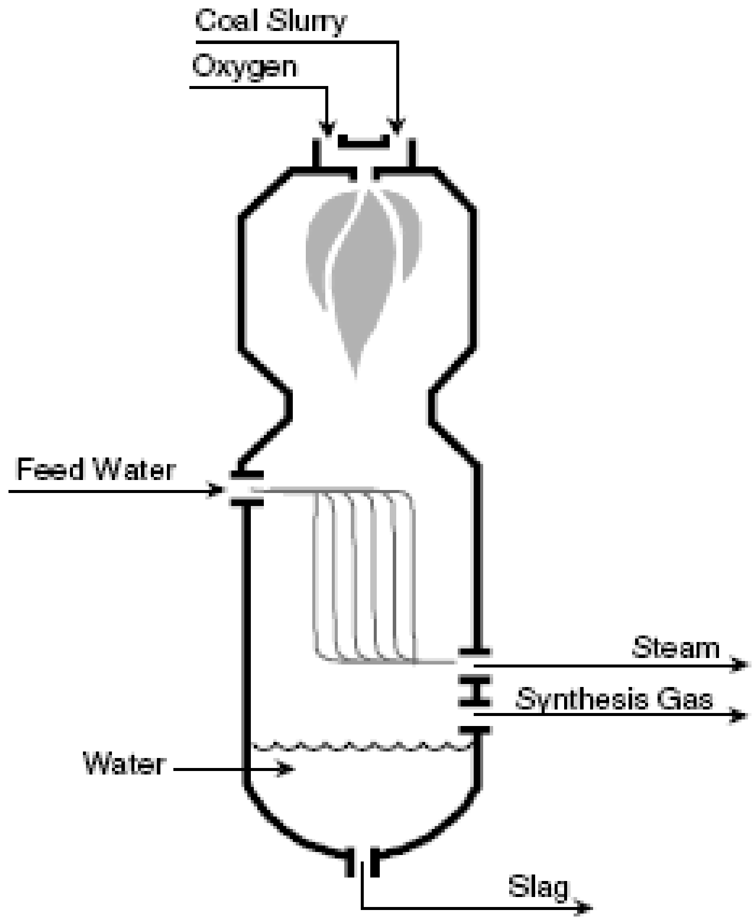


FIGURE 5-32. Schematic diagram of the ChevronTexaco gasifier. (From Ratafia-Brown, J. *et al.*, *Major Environmental Aspects of Gasification-Based Power Generation Technologies*, Office of Fossil Energy, U.S. Department of Energy, Washington, D.C., December 2002.)

Shell Gasifier

- The Shell gasifier, the successor to the Koppers–Totzek process and then the Shell–Koppers process, is shown schematically in Figure 5-33 and is a dry-feed, pressurized, entrained-flow, slagging gasifier that can operate on a wide variety of feedstocks.
- Pulverized coal is pressurized in lock hoppers and fed to the gasifier by dense-phase conveying with transport gas, which can be nitrogen or syngas.
- Preheated oxygen is mixed with steam and used as a temperature moderator prior to feeding to the fuel injector.
- Temperatures and pressures in the gasifier are 2700 to 2900°F and 350 to 650 psig, respectively.
- A syngas is produced that contains mainly hydrogen and carbon monoxide with little carbon dioxide.

Shell Gasifier

- Elevated temperatures eliminate the production of hydrocarbon gases and liquids in the product gas.
- The high temperature converts the ash into molten slag, which runs down the refractory walls into a water bath, where it is quenched and the ash/water slurry is removed through a lock hopper.
- The raw gas leaving the gasifier at 2500 to $3000^{\circ}F$ contains a small quantity of char and about half of the molten ash.
- The hot gas is partially cooled to temperatures below the ash fusion point by quenching it after it leaves the gasifier.
- The syngas undergoes further cooling before the particles are removed in a wet scrubber.
- The first Shell gasification process units were commissioned in the 1950s.
- Shell started development work with coal in 1972.

Shell Gasifier

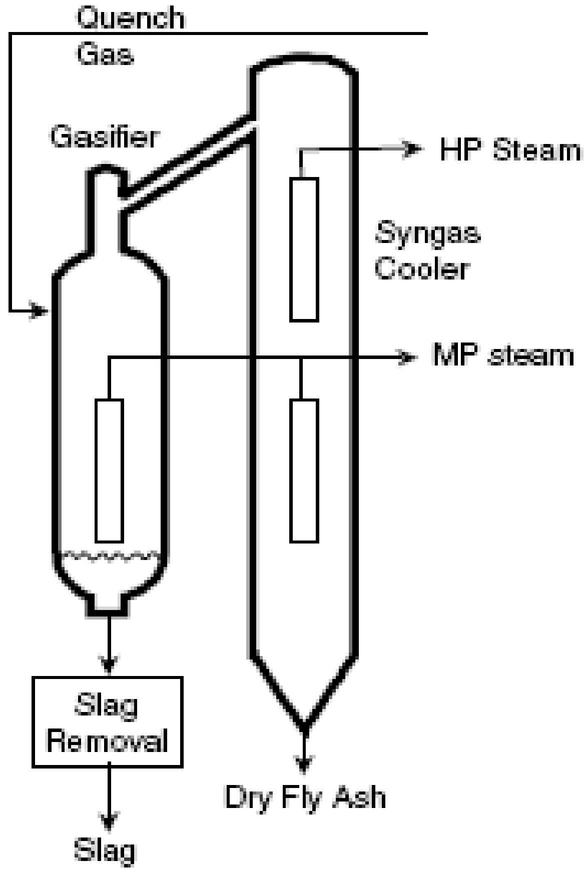
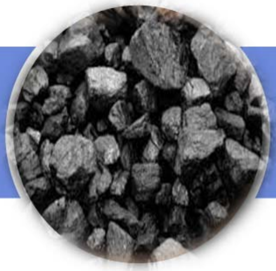


FIGURE 5-33. Schematic diagram of the Shell gasifier. (From Ratafia-Brown, J. *et al.*, *Major Environmental Aspects of Gasification-Based Power Generation Technologies*, Office of Fossil Energy, U.S. Department of Energy, Washington, D.C., December 2002.)

Prenflo Gasifier

- The Prenflo gasifier, developed by Uhde (formerly Krupp Uhde) and shown schematically in Figure 5-34, is a pressurized, dry-feed, entrained-flow, slagging gasifier.
- Coal, ground to $\sim$100 μm, is pneumatically conveyed by nitrogen to the gasifier. The coal is fed through injectors located in the lower part of the gasifier with oxygen and steam.
- Syngas, produced at temperatures of $\sim 2900^{\circ}$F, is quenched with recycled cleaned syngas to reduce its temperature to $\sim 1500^{\circ}$F in an internal syngas cooler.
- The syngas is further cooled to $\sim 700^{\circ}$F through evaporator stages before exiting the gasifier.
- The molten slag flows down the walls into a water bath, where it is quenched and granulated before removal through a lock hopper system.

Prenflo Gasifier



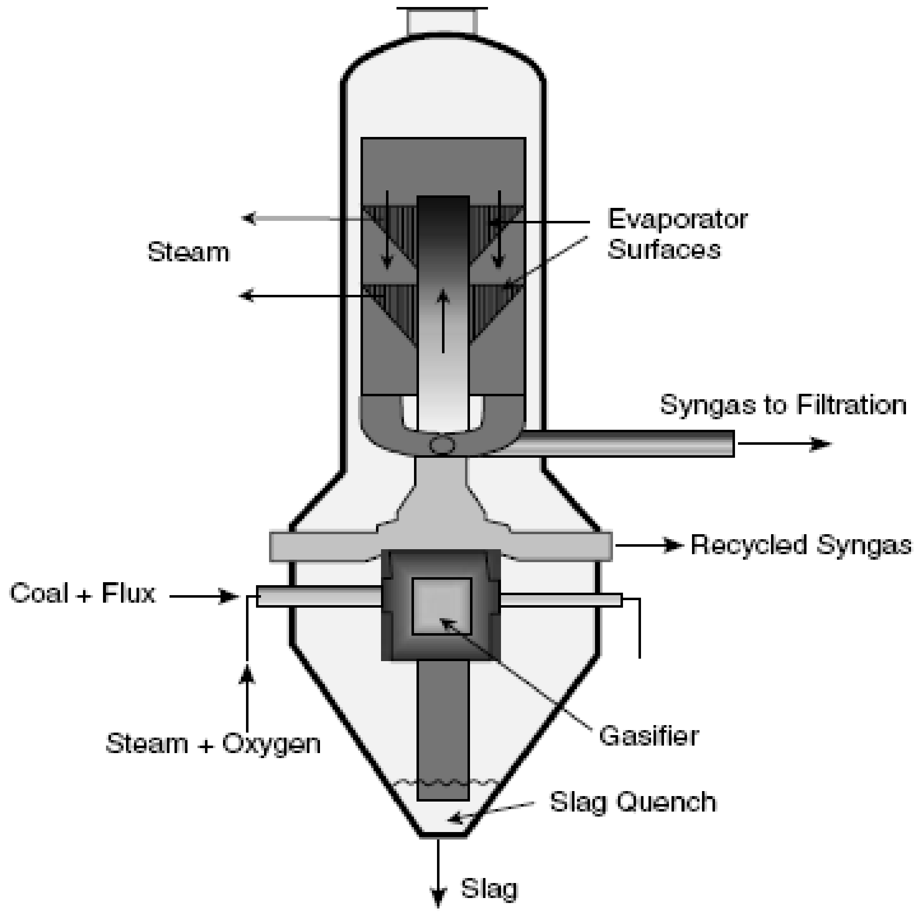


FIGURE 5-34. Schematic diagram of the Prenflo gasifier. (From Ratafia-Brown, J. *et al.*, *Major Environmental Aspects of Gasification-Based Power Generation Technologies*, Office of Fossil Energy, U.S. Department of Energy, Washington, D.C., December 2002.)

E-Gas Gasifier

- The E-Gas gasifier, shown schematically in Figure 5-35, is a slurry-feed, pressurized, entrained-flow gasifier.
- It is an upward flow gasifier with two-stage operation.
- The coal is slurried via wet crushing, with coal concentrations ranging from 50 to 70 wt.%, and about 75% of the total slurry feed is fed to the first stage of the gasifier, which operates at 2600°F and of the gasifier, where the highly exothermic gasification/oxidation reactions occur.
- Operation at the elevated temperatures eliminates the production of hydrocarbon gases and liquids in the product gas.

E-Gas Gasifier

- The molten ash flows into a water bath, where it is quenched and removed.
- The raw gas from the first stage enters the second stage, where the remaining 25% coal slurry is injected.
- The endothermic gasification/devolatilization reactions occur in this stage at a temperature of $\sim 1900^{\circ}$F, and some hydrocarbons are added to the product gas.
- Char is produced in the second stage and is recycled to the first stage, where it is gasified.
- The syngas exits the gasifier and undergoes further cooling and cleaning.

E-Gas Gasifier

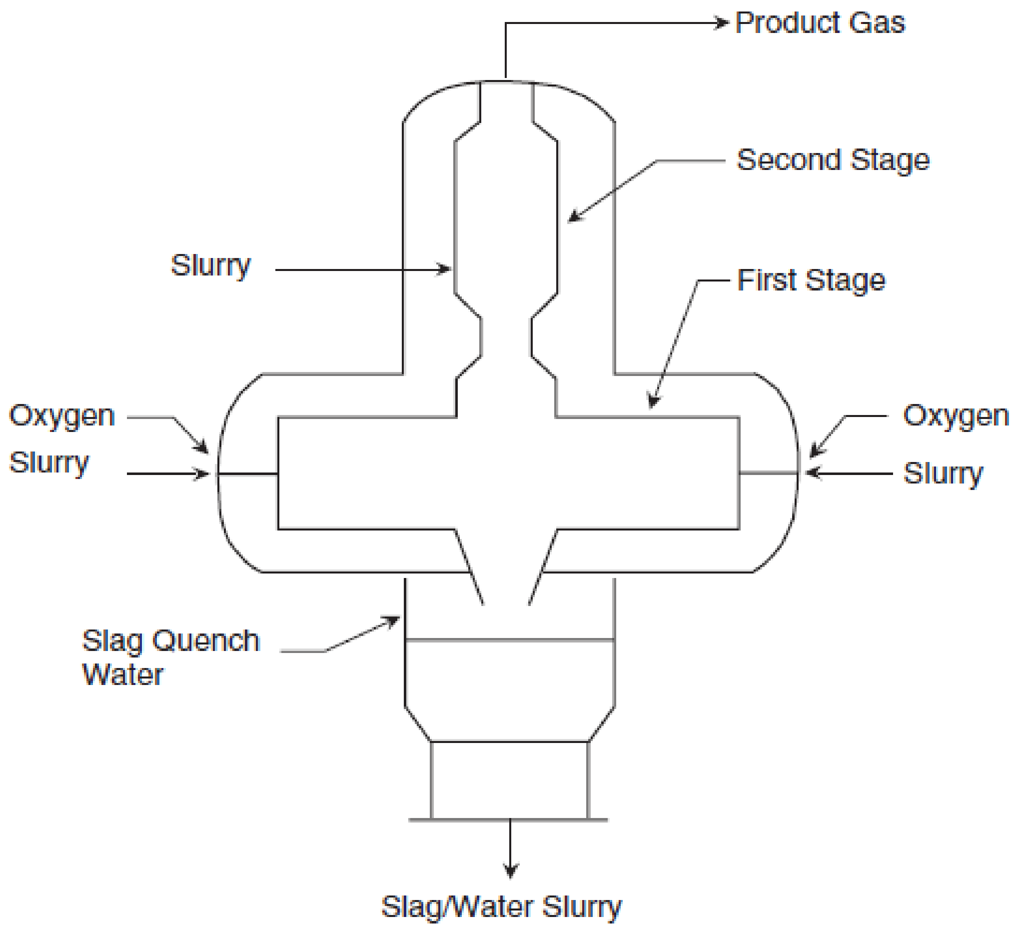


FIGURE 5-35. Schematic diagram of the E-Gas gasifier. (From Ratafia-Brown, J. *et al.*, *Major Environmental Aspects of Gasification-Based Power Generation Technologies*, Office of Fossil Energy, U.S. Department of Energy, Washington, D.C., December 2002.)