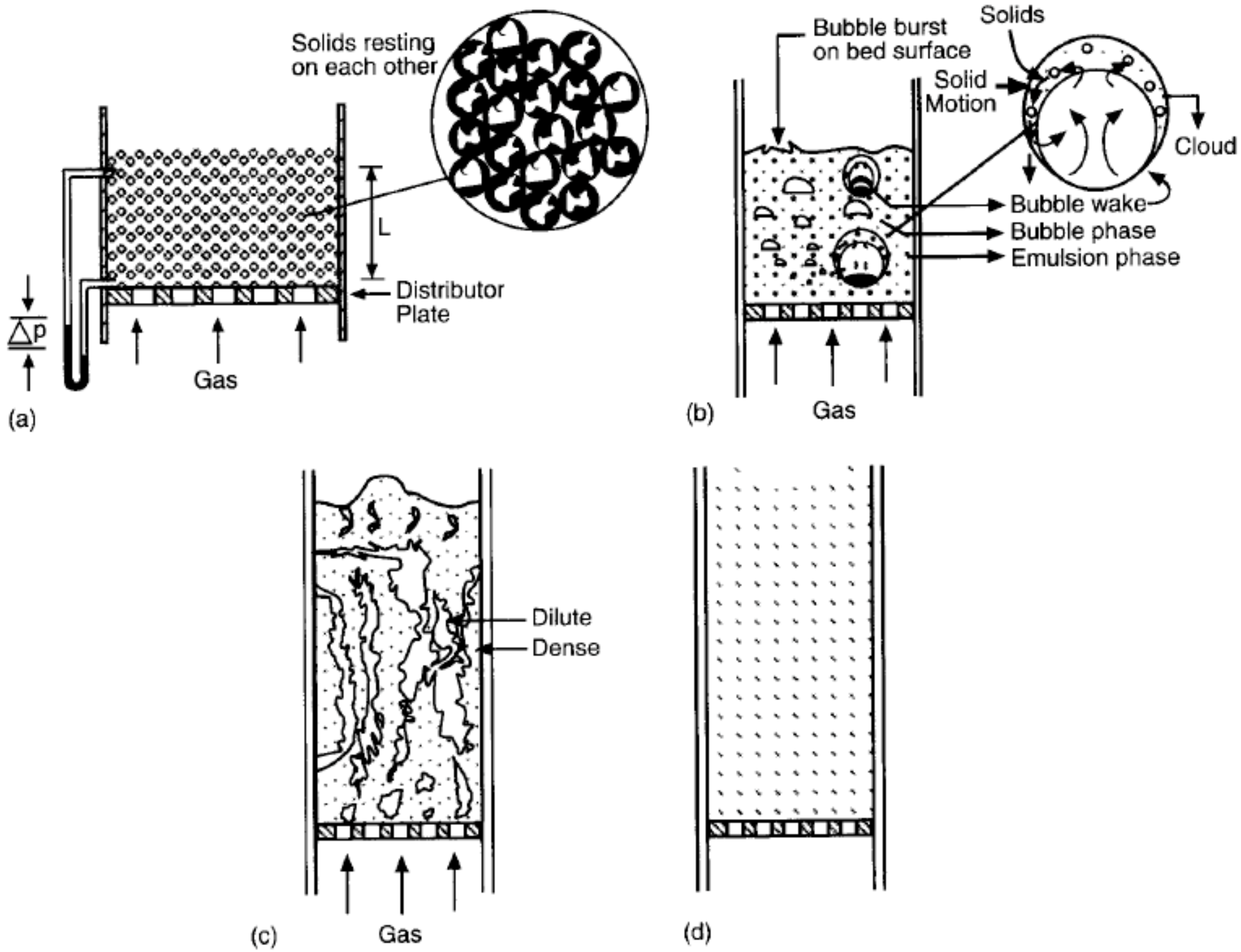
# Gasification processes

# Reactor types

- Moving bed (or fixed bed): the solid fuel moves by gravity
- Fluid bed: the solid fuel is suspended by the fluid
- Entrained flow: the solid flows in the same direction as the fluid

# Fluidization regimes



# Gasification processes

**Table 5-1**
**Characteristics of Different Categories of Gasification Process**

| **Category** | **Moving-Bed** | | **Fluid-Bed** | | **Entrained-Flow** |
|---|---|---|---|---|---|
| Ash conditions | Dry ash | Slagging | Dry ash | Agglomerating | Slagging |
| Typical processes | Lurgi | BGL | Winkler, HTW, CFB | KRW, U-Gas | Shell, Texaco, E-Gas, GSP, KT |
| **Feed characteristics** | | | | | |
| Size | 6–50 mm | 6–50 mm | 6–10 mm | 6–10 mm | <100 μm |
| Acceptability of fines | limited | better than dry ash | good | better | unlimited |
| Acceptability of caking coal | yes (with stirrer) | yes | possibly | yes | yes |
| Preferred coal rank | any | high | low | any | any |
| **Operating characteristics** | | | | | |
| Outlet gas temperature | low (425–650°C) | low (425–650°C) | moderate (900–1050°C) | moderate (900–1050°C) | high (1250–1600°C) |
| Oxidant demand | low | low | moderate | moderate | high |
| Steam demand | high | low | moderate | moderate | low |
| Other characteristics | hydrocarbons in gas | hydrocarbons in gas | lower carbon conversion | lower carbon conversion | pure gas, high carbon conversion |

*Source: Adapted from Simbeck et al. 1993*

# Moving bed processes

- Producer gas
- Water gas
- The Lurgi Dry Ash Process

# Producer gas

- Humidified air is blown upwards through a deep bed of coal or coke.
- Coal is fed from the top and moves slowly downwards
- Ash is drawn off at the bottom
- Air reacts with coal producing a gas with LHV of 6500 kJ/m3 and with low rank coals or biomass to produce a gas with LHV of 3500 kJ/m3
- It is a continuous process

# Water gas

- It is a discontinuous process
  - First air is passed upwards to start combustion up to 1300 °C to have a red-hot coke
  - Then steam is passed upwards and downwards to form H2 and CO until 900 °C are reached
- Before large scale separation plants it was the only process to produce synthesis gas for chemical purposes

# The Lurgi Dry Ash Process

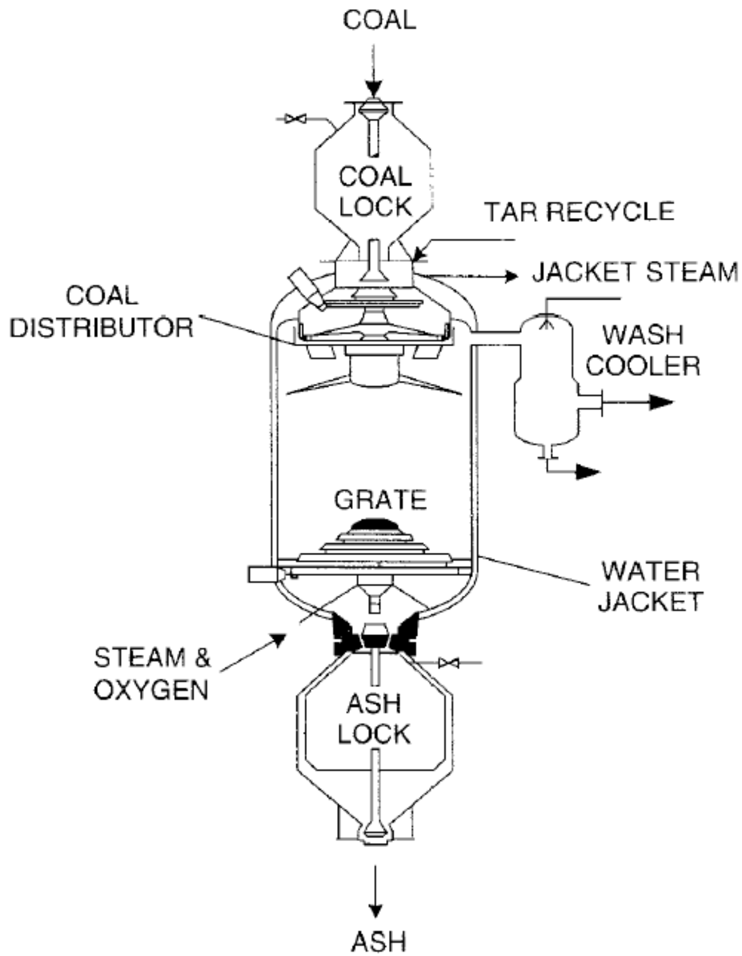
- Developed in 1931 in Germany: TU Berlin
- First application in 1936 and in 1944 two large scale applications to produce town gas
- It has been the only pressurized gasifier for many years 25-30 bar and one at 100 bar

**Sizes and Capacities of Lurgi Dry Ash Gasifiers**

| Type | Nominal Diameter (m) | Coal Throughput (t/h) | Gas Production (Dry) (1000 $Nm^3$/day) |
|---|---|---|---|
| MK III | 3 | 20 | 1000 |
| MK IV | 4 | 40 | 1750 |
| MK V | 5 | 60 | 2750 |

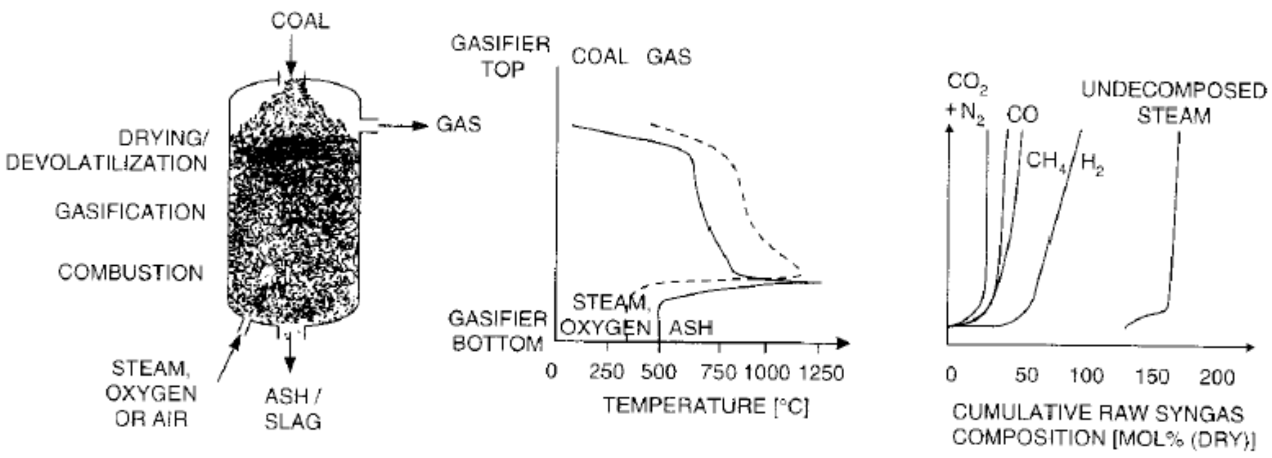
# Principle of operation

- Blast and syngas flow upwards and the solid fuel downwards
- The lock hopper is opened and then closed and pressurized with syngas thus feeding the reactor cyclically
- The vessel is jacketed and the jacket is filled with boiling water that cools the reactor and generates steam
- Steam has the pressure of the gasifier and there is no need for a thick wall between reactor and boiling water: heat transfer improved.
- Ash is removed from the bottom



# Reactions

- The blast enters at the bottom and reacts with the the char to CO2 giving the highest temperature
- CO2 and steam react in the gasification zone to give H2 and CO: high steam and low O2 demand
- The gas composition is governed by the water-gas, the Bouduard and methanation reactions
- The gas leaving the gasification zone is used to devolatilize, preheat and dry the incoming fuel and is cooled from 800 to 550 °C
- The result is a high methane content and many others substances such as phenols, ammonia and hydrocarbons

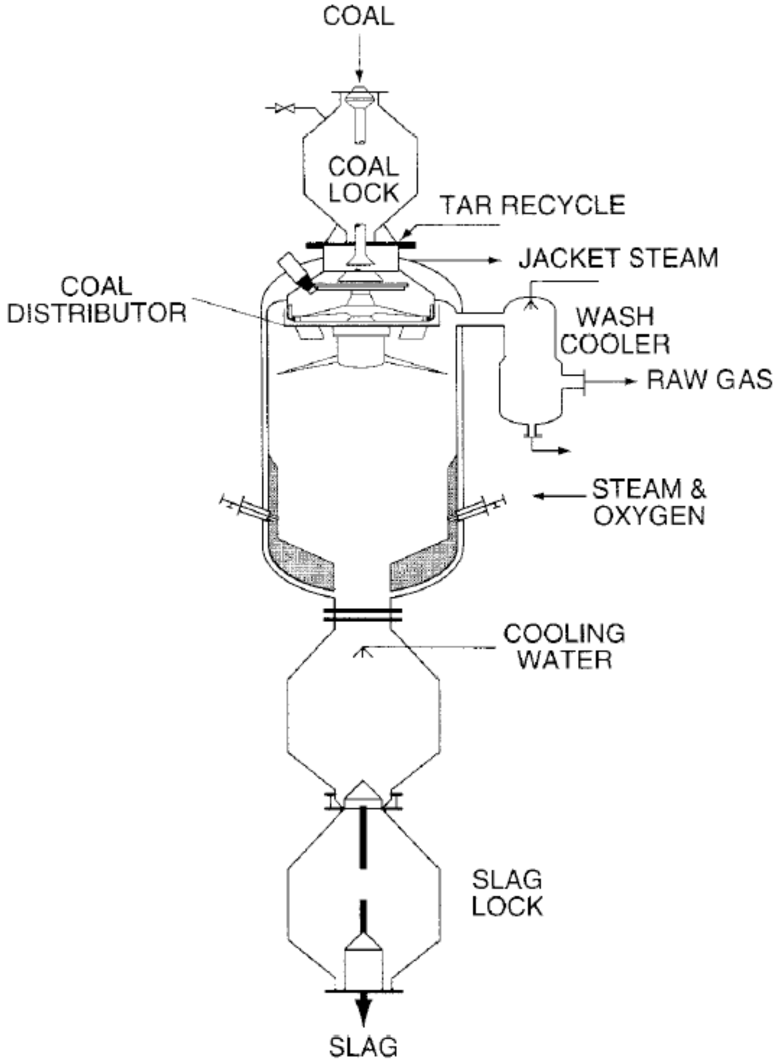


# Applications

- The most important installation forms part  of the Sasol synthetic fuels in South Africa are 13 MK III, 83 MK IV and 1 MK V reactors, producing 55 millions M3/day syngas to produce 170.000 bls/day of Fischer Tropsch liquid fuels
- In the US production of substitute natural gas
- Some gas to gas turbines in Germany and Czech republic

# BGL Slagging Gasifier

- BGL is an extension of the Lurgi process developed by British Gas with ashes in slaggin conditions.
- The aims were:
  - To increase CO and H2 yields
  - Increase reactor throughput
  - Using coals with low ash melting points
  - Reactor suitable to accepting fines
  - Reduce steam consumption



# The performance

**Typical Performance Data of Lurgi Dry Ash Gasifier**

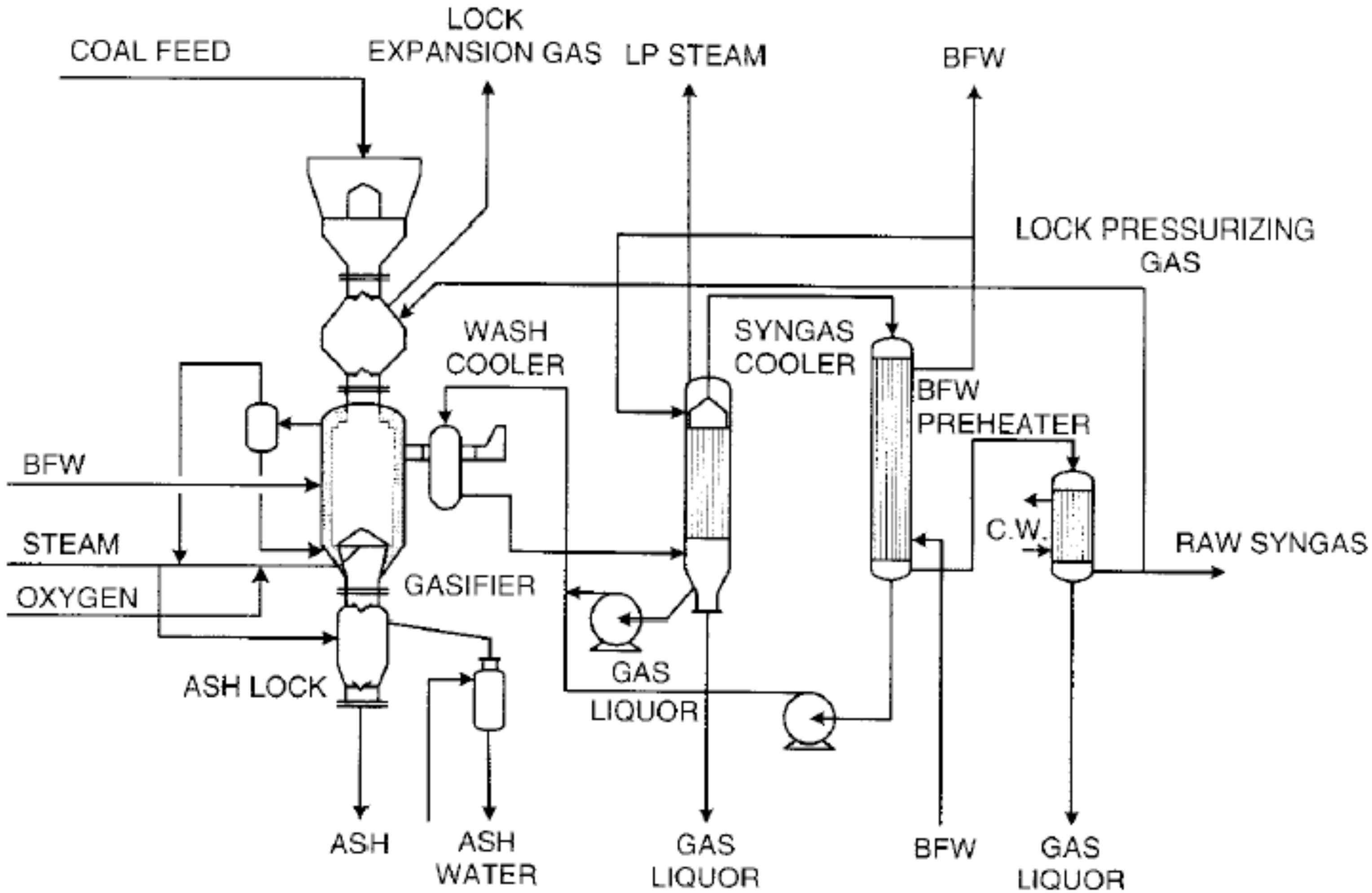
| Type of Coal | Lignite | Bituminous | Anthracite |
|---|---|---|---|
| **Components (maf)** | | | |
| C, wt% | 69.50 | 77.30 | 92.10 |
| H, wt% | 4.87 | 5.90 | 2.60 |
| S, wt% | 0.43 | 4.30 | 3.90 |
| N, wt% | 0.75 | 1.40 | 0.30 |
| O, wt% | 24.45 | 11.10 | 1.10 |
| **Raw gas composition (dry)** | | | |
| $CO_2 + H_2S$, mol% | 30.4 | 32.4 | 30.8 |
| CO, mol% | 19.7 | 15.2 | 22.1 |
| $H_2$, mol% | 37.2 | 42.3 | 40.7 |
| $CH_4$, mol% | 11.8 | 8.6 | 5.6 |
| $C_nH_m$, mol% | 0.4 | 0.8 | 0.4 |
| $N_2$, mol% | 0.5 | 0.7 | 0.4 |
| **Feed components per 1000 $Nm^3$ $CO+H_2$** | | | |
| Coal maf, kg | 950 | 750 | 680 |
| Steam, kg | 1180 | 1930 | 1340 |
| Oxygen, $Nm^3$ | 170 | 280 | 300 |

# Example in waste gasification

| | | |
|---|---|---|
| Mixed Fuel (ar) | 30 | t/h |
| Specific oxygen consumption | <0.2 | $Nm^3/Nm^3$ dry syngas |
| Gasification agent ratio steam/oxygen | <1.0 | $kg/Nm^3$ dry syngas |
| Raw syngas (dry) | 31,500 | $Nm^3/h$ |

- Coal and waste gasification: 25% coal, 45% RDF, 10% plastic, 10% wood, 10% tar sludge
- Gasification pressure 25 bar
- Disposal requirements of slag according to German regulations

# Process flowsheet

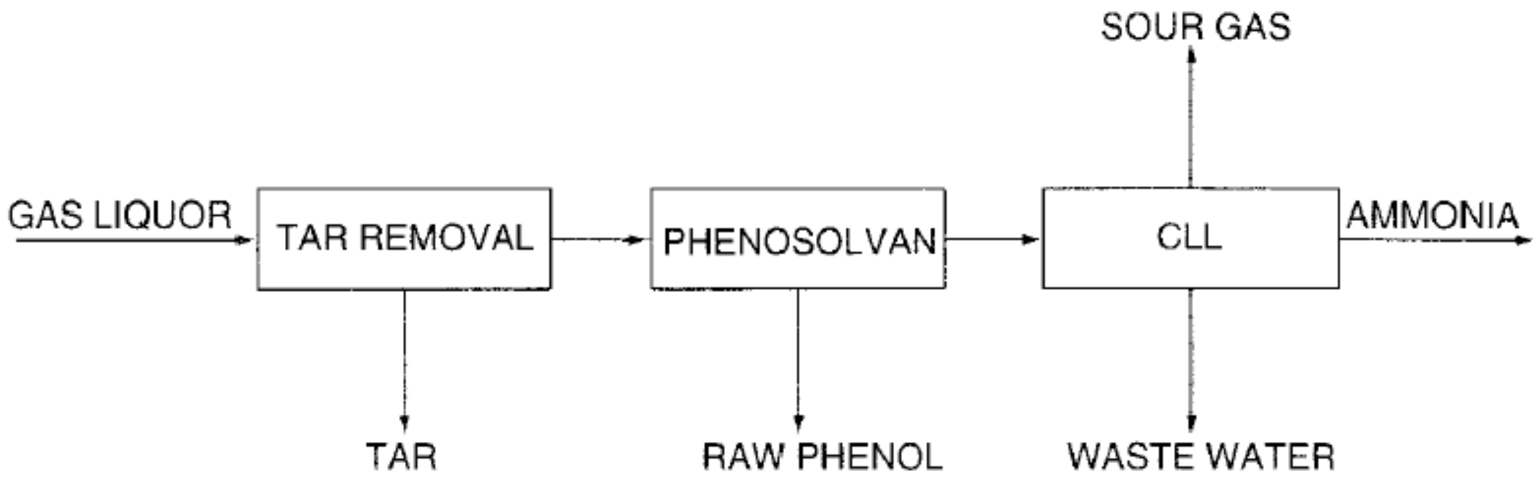


# Gas liquor

**Gas Liquor Composition**

| | | |
|---|---|---|
| Suspended Matter | 1000 | mg/l |
| Sulfur | 600 | mg/l |
| Chloride | 50 | mg/l |
| $NH_3$ and $NH_4$ ions | 10,000 | mg/l |
| Cyanide | 50 | mg/l |
| Phenols | 1000–5000 | mg/l |
| COD | 10,000 | mg $O_2$/l |

- Mechanical tar separation
- Phenols extraction
- Sour gas and ammonia are separated and sour gas treated in a Claus unit
- Good quality ammonia recovery

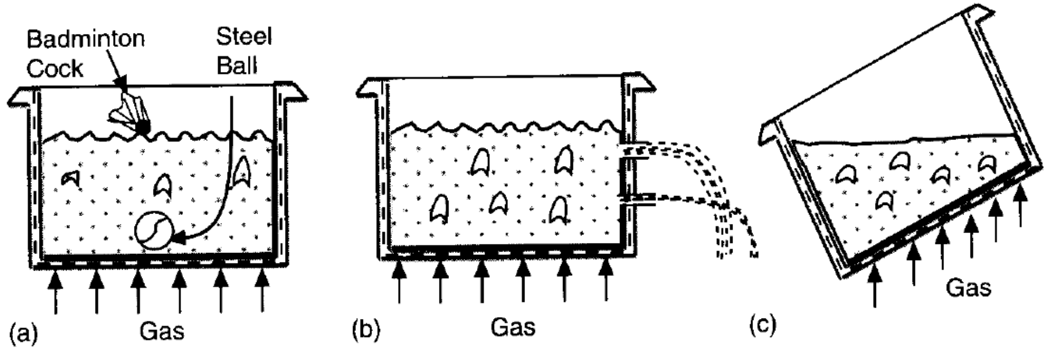


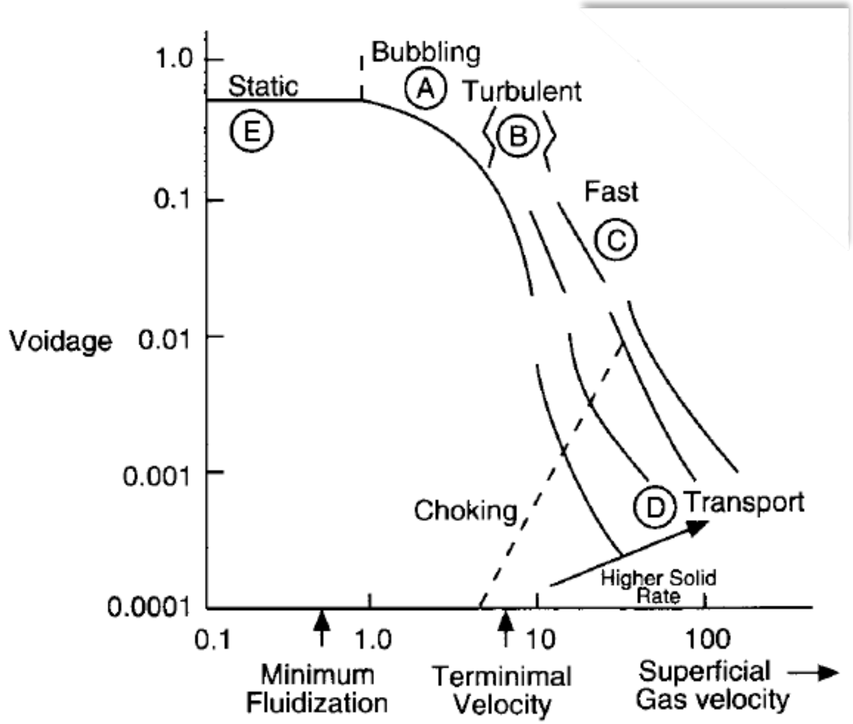
# Fluidized bed gasification

# Fluidization

- Fluidization is the operation by which fine solids are transformed into a fluid-like state through contact with a gas or liquid
- In a fluidized bed, the gravitational pull on fluidized particles is offset by the upward fluid drag on the gas, keeping the particles in suspended condition with the following properties:
  - The static pressure at any height is approximately equal to the weight of bed solids per unit area above that level
  - An object denser than the bed will sink, an object lighter will float
  - The solids can be drained from the bed like a liquid through an orifice at the bottom or on the side of the container
  - The bed surface maintains a horizontal level, independent of how the bed is tilted and the bed has the shape of the container
  - Particles are well mixed and the bed maintains a nearly uniform temperature

# Fluidization



# Bubbling fluidized bed

- When the gas velocity reaches a critical value known as the minimum fluidization velocity, when the fluid drag is equal to the particle's weight less its buoyancy, the fixed bed becomes a fluidized bed
- Since the pressure drop across the bed equals the weight of the bed, the fluid drag force can be written:

$$F_D = \Delta PA = AL(1-\varepsilon)(\rho_p-\rho_g)g$$

- Where A and L are the cross-sectional area and height of the bed.
- The minimum fluid velocity at which the bed becomes fluidized is obtained by:

$$\mathrm{Re}_{mf} = \frac{U_{mf} d_p \rho_g}{\mu} = [C_1^2 + C_2 \mathrm{Ar}]^{0.5} - C_1$$

- Where:

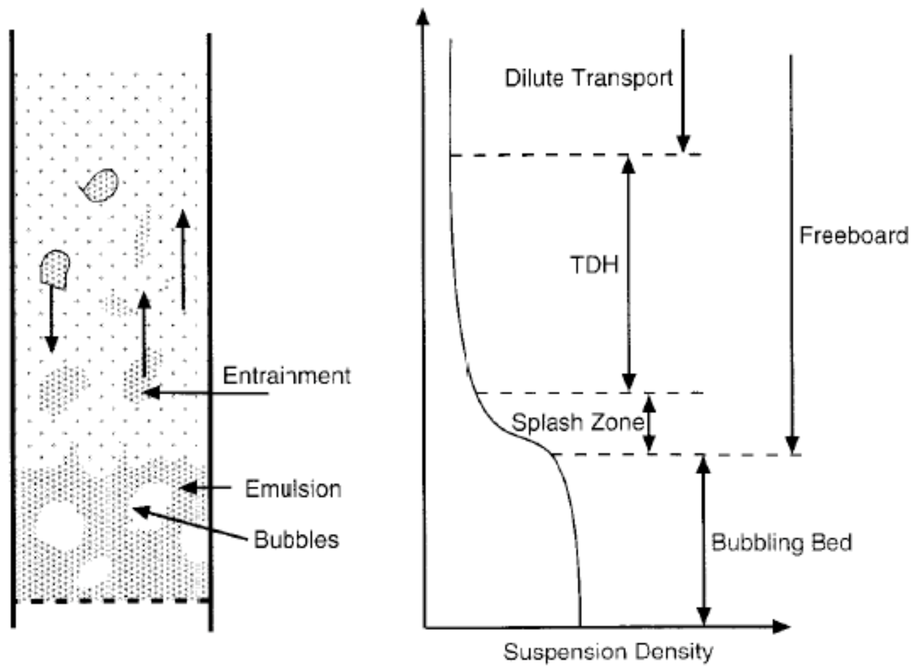
$$\mathrm{Ar} = \frac{\rho_g(\rho_p-\rho_g)g d_p^3}{\mu^2}$$

- But bubbles start to appear when the fluid velocity reaches:
-

$$U_{mb} = 2.07 \exp(0.716F) d_p \left[ \frac{\rho_g^{0.06}}{\mu^{0.347}} \right]$$

# Bubbling fluidized bed

- Bubbles are gas voids with little or no solids
- Bubbles rise due to buoyancy force through the emulsion phase
- Bubble size increases with particle diameter, velocity and distance from the bottom of the bed
- The gas passing through the emulsion phase is less than that passing through the bubbles.
- Bubbles are a major by-passing reason for oxygen and fines
- The emulsion phase does not rise over the bed.
- Bubbles carry some solids upwards in its wake. The lighter particles travel up over the TDH (Transport disengaging zone) and the heavier fall down to the bed



# Turbulent beds

- When the velocity of gas is increased above the minimum bubbling velocity the bed starts expanding
- Increasing the velocity further expands the emulsion phase and makes the emulsion walls thinner, with a highly expanded bed with a surface considerably diffused.
- The lower part of most CFB boilers/gasifiers has this flow regime
- The transition from bubbling to turbulent appears at the surface and move downwards

# Terminal velocity of a particle

- When a fluid has a different velocity than that of a particle moving in the same direction of the fluid the particle experiences a drag force:

$$F_D = C_D \frac{\pi d_p^2}{4} \left( \frac{\rho_g U^2}{2} \right)$$

- Where $C_D = \dfrac{a_1}{\mathrm{Re}^{b_1}}$

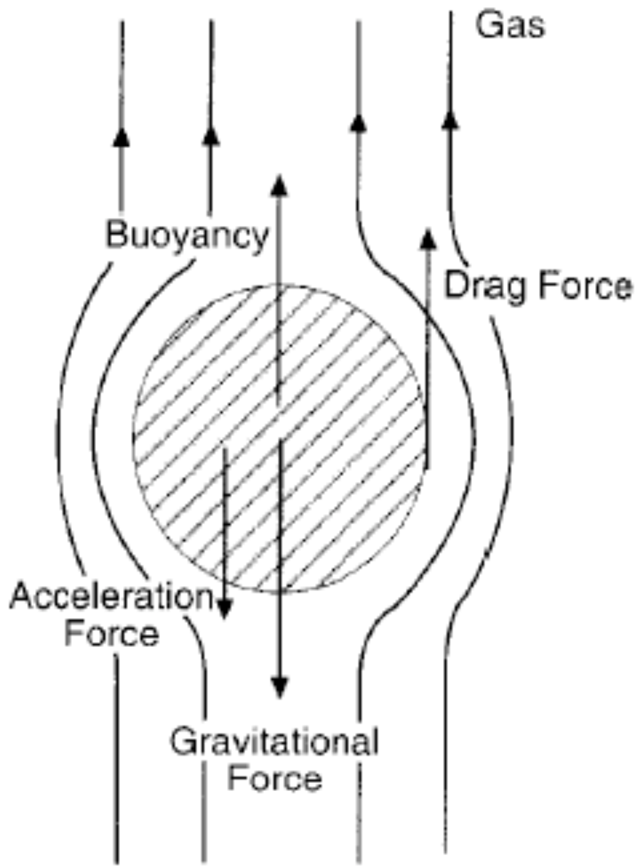
| Range of Re | Region | $a_1$ | $b_1$ |
|---|---|---|---|
| $0 < \mathrm{Re} < 0.4$ | Stoke's law | 24 | 1.0 |
| $0.4 < \mathrm{Re} < 500$ | Intermediate law | 10 | 0.5 |
| $500 < \mathrm{Re}$ | Newton's law | 0.43 | 0.0 |

- Thus the force balance gives:

Gravitational force = Buoyancy Force + Drag Force

$$m_p g = m_p \frac{\rho_g g}{\rho_p} + C_D \frac{\pi (U - U_s)^2 \rho_g}{8} d_p^2$$

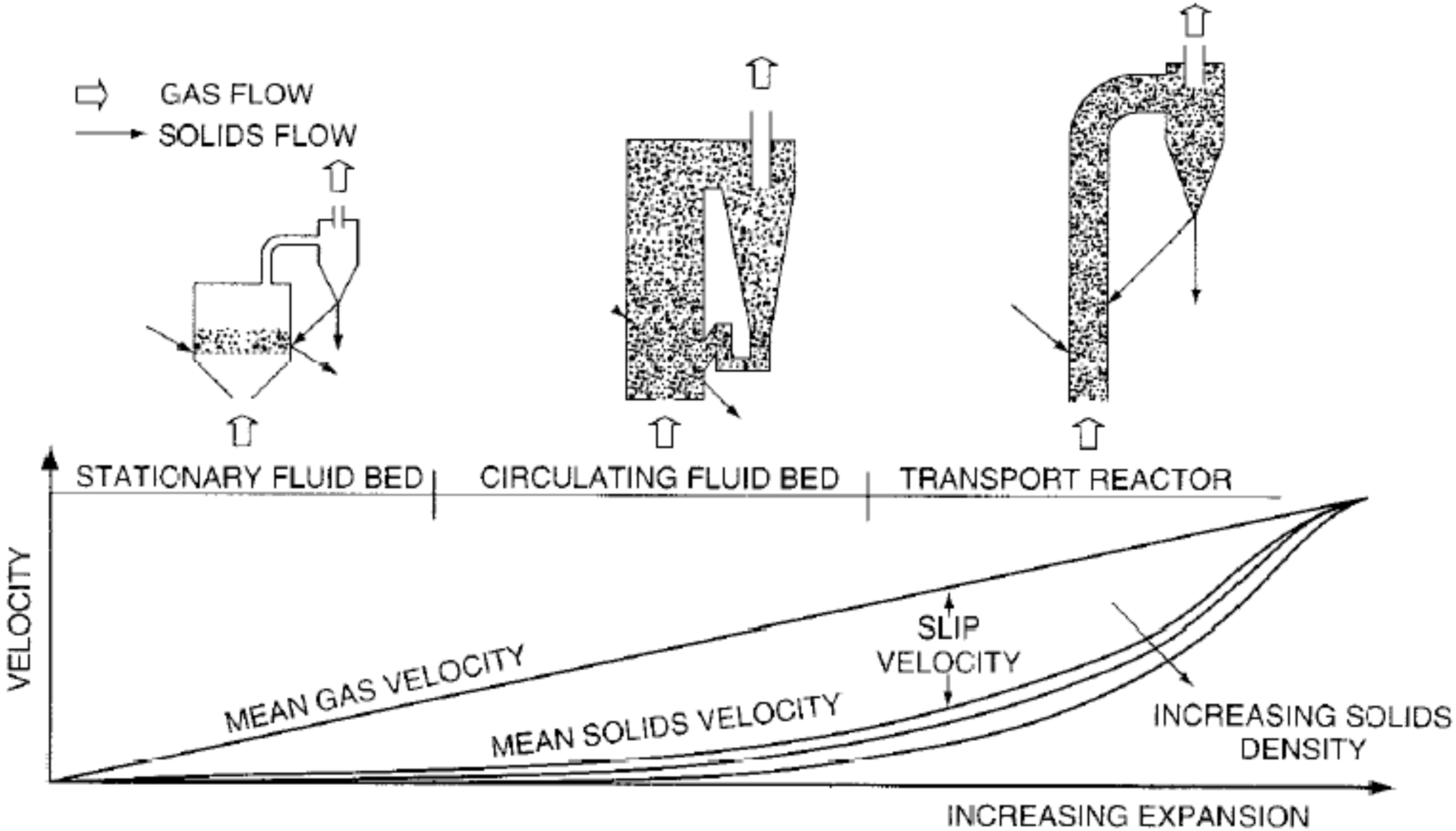
The particle velocity when U=0 is called the terminal velocity



# Historical notes

- The history of fluidized bed gasification is linked with the Winkler process developed in the 1920s.
- Winkler's process featured a clear distinction between a dense phase bed and a freeboard where the particles disengage from the gas
- This regime is the stationary fluid bed, but when the velocity increases the differential velocity between fluid and particles reaches a maximum as in a circulating fluid bed
- Higher velocities are reached in an entrained fluid bed
- In fluid bed gasification the blast has to act as fluidizing medium and as reactant

# Fluid bed types



# Operating temperature

- A large portion of the solids content of the bed of a gasifier is ash.
- If the ash begins to soften and to agglomerate these larger particles will obstruct the distribution grid and block the blast flow
- For this reason fluid bed gasifiers operate below the softening temperature of ashes (950-1100 °C for coal and 800-950°C for biomass)
- If gasification temperatures are too low, more tars will be produced because of a slower heating of the solids and of a reduced cracking of the tars produced.
- The best known fluid bed gasifiers are the regenerators of catalytic cracking which operate under reducing conditions in refineries

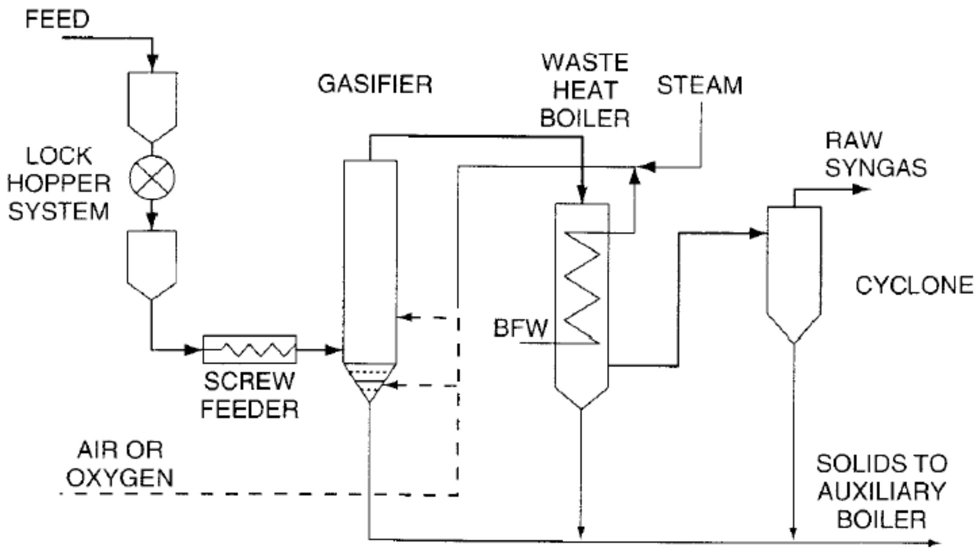
# Feed quality and ashes

- Historically fluid bed gasifier have been used for low rank coals and biomass. Low rank coals have a higher reactivity which compensates the lower temperature.
- Maximum size of the fuel should be lower than 10mm but also fuels with an excess of fines should be avoided
- Problems of fines are particularly severe in bubbling beds
- Most fluid bed have a carbon conversion efficiency higher than 97%, and in many cases of 99%
- Ash can be removed dry or wet and generally contain large amounts of limestone for sulphur removal

# The Winkler process

- The Winkler process was the first gasification process to use oxygen instead of air
- Patented in 1922, first plant in 1925, since then more than 70 plants have been built
- Now all the plants but one have been closed for economic reasons
- The Winkler works with any coal but it requires a good preparation with particles smaller than 10 mm
- It does not require drying if moisture content is lower than 10%

# The Winkler process




- The fuel is introduced by a screw conveyor
- The blast is introduced through the bottom grate at 5 m/s and in the middle of the bed
- The bed is refractory lined
- Operation is below the ash melting point and between 950-1050 °C
- 20% of the carbon is unreacted and is burnt in the waste heat boiler

# Process performance

**Table 5-6**
**Typical Performance for Fluid-Bed Gasifiers for Different Feedstocks and Blasts**

| Type of Coal | | Biomass | Lignite | Bituminous | Bituminous |
|---|---|---|---|---|---|
| Blast | | Air | $O_2$/steam | $O_2$/steam | Air |
| Temperature | °C | 900 | 1000 | 1000 | 1000 |
| Pressure | bar | 30 | 30 | 30 | 30 |
| **Components (maf)** | | | | | |
| C, wt% | | 50.45 | 66.66 | 81.65 | 81.65 |
| H, wt% | | 5.62 | 4.87 | 5.68 | 5.68 |
| S, wt% | | 0.10 | 0.41 | 1.13 | 1.13 |
| N, wt% | | 0.10 | 1.14 | 1.71 | 1.71 |
| O, wt% | | 43.73 | 26.92 | 9.83 | 9.83 |
| **Raw gas composition(dry)** | | | | | |
| $CO_2$, mol% | | 6.7 | 6.2 | 5.3 | 1.9 |
| CO, mol% | | 31.0 | 56.7 | 52.0 | 30.7 |
| $H_2$, mol% | | 18.9 | 32.8 | 37.3 | 18.7 |
| $CH_4$, mol% | | 2.1 | 2.6 | 3.5 | 0.9 |
| A, mol% | | 0.5 | 0.6 | 0.6 | 0.6 |
| $N_2$, mol% | | 40.8 | 0.9 | 1.0 | 47.0 |
| $H_2S$, mol% | | 0.03 | 0.2 | 0.3 | 0.2 |
| **Feed components per 1000 $Nm^3$ $H_2+CO$** | | | | | |
| Fuel maf, kg | | 893 | 777 | 517 | 516 |
| Steam, kg | | 0 | 1 | 213 | 112 |
| Air or Oxygen, $Nm^3$ | | 1358 | 339 | 324 | 1581 |

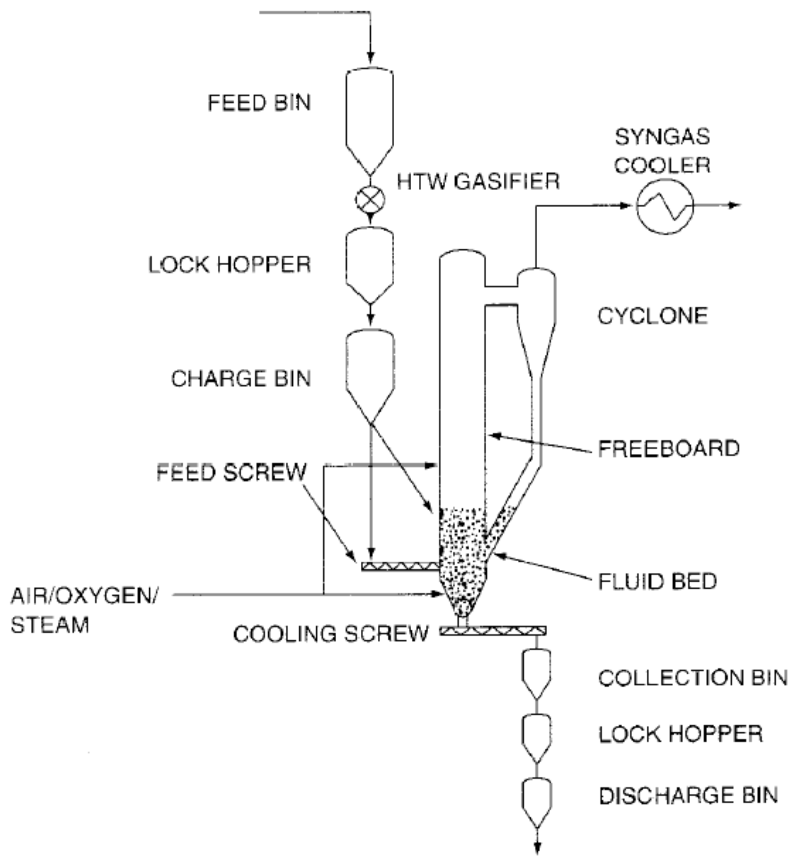
*Note: Biomass is dry wood. Oxygen purity is 95 mol%. Air preheat is 400°C, Oxygen preheat is 200°C.*

# High Temperature Winkler

- The process was developed by Rheinbraun for the gasification of lignite
- Rheinbraun is a lignite producer in Germany that started the gasification activities in 1970 and a subsidiary Union Kraftstoff had already experience with atmospheric Winkler processes
- The focus was on methanol and hydrogen production for the development of an hydrogenating gasifier for SNG production
- In fact it is not the temperature that is increased but the pressure: 30 bar
- The idea was to raise temperature and pressure and use the solid recycle from the cyclone

# High Temperature Winkler

- The feed system includes a lock hopper to pressurize the screw
- The syngas cooler cools the gas from 900 to 300 °C
- A ceramic candle filter is used to clean the gas after the syngas cooler



# Applications

- One 600 t/d 10 bar unit was operated for 12 years in Berrenrath to provide gas for methanol synthesis
- A similar plant with 13.5 bas was operated with peat in Finland
- A 160 t/d was operated in Wesseling at 25 bar to study the application of IGCC
- Two 980 t/d are under construction in Vresova in the Czech Republic to replace 26 fixed bed gasifiers to provide syngas to an IGCC
- A 20 t/d for waste gasification has been built in Japan

# CFB Processes

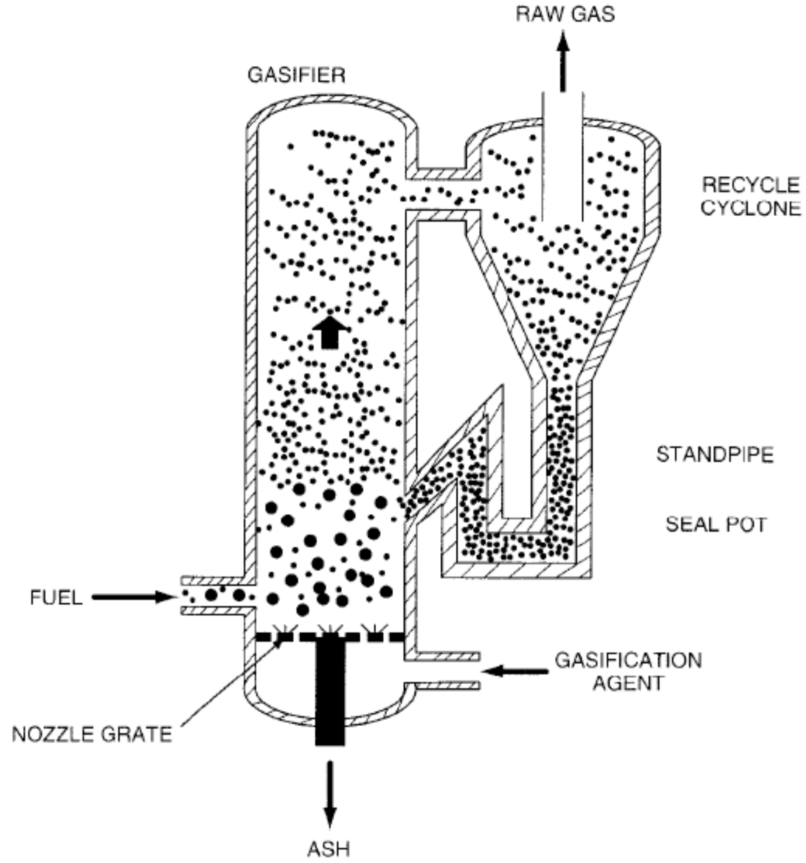
- Good mixing of solids and gas with good heat and mass transfer
- Small particles react and are entrained by the gas and separated in the cyclone
- Larger particles are consumed in the bed until they become small enough to be entrained
- Tar formation is greatly reduced in comparison with fixed bed
- Recent transport reactors are very efficient in carbon conversion
- The CFB is less critical than bubbling beds for the size and shape of particles

# CFB Processes

- Two companies produce CFB gasifiers: Lurgi and Foster Wheeler
- The Lurgi atmospheric CFB was first produced for aluminium processes and then developed for biomass gasification
- The Foster Wheeler (originally Ahlstrom) was developed for biomass gasification for Scandinavian forest industry

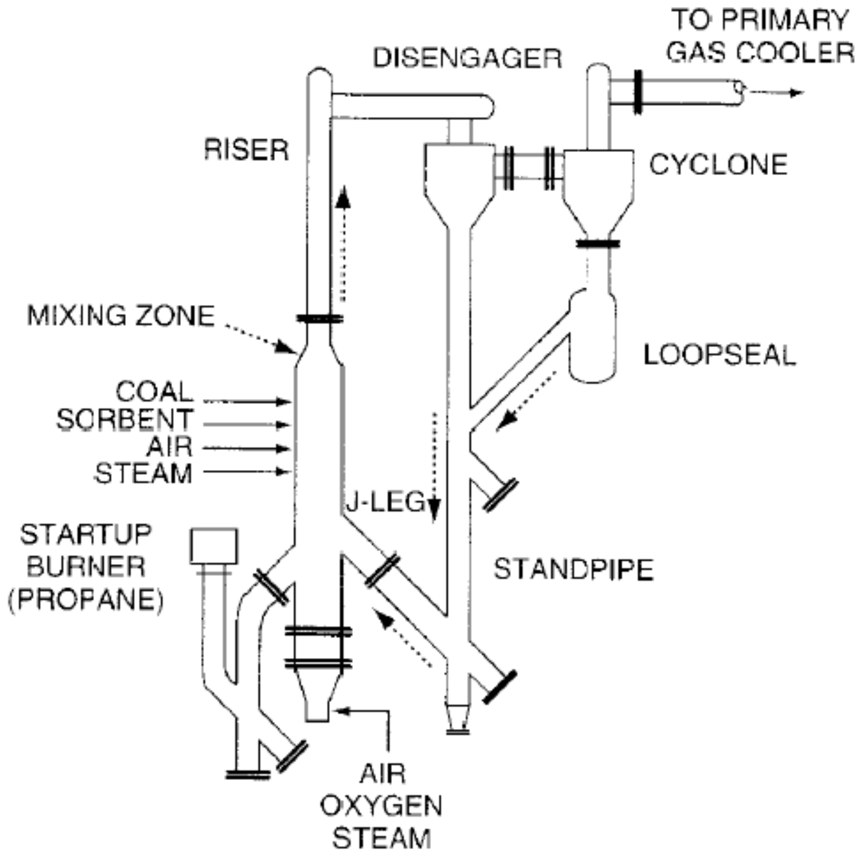
# Lurgi CFB

- The BCF includes a reactor, a cyclone and a seal pot
- The velocities are 5-8 m/s to entrain larger particles
- The solids captured in the cyclone are returned in the seal pot
- The gasifying agent (air) is introduced at the bottom and over the fuel
- For biomass the fuel size must not exceed 25-50 mm



# Kellogg Brown & Root Process

- Higher velocities of 11-18 m/s to demonstrate higher circulation rates, velocities and riser densities
- Temperature between 900 and 1100 °C
- Pressure 11-18 bar
- Fuel and sorbent are introduced through separate lock hoppers and mixed with the blast
- The blast is a mixture of oxygen and steam or air and steam
- The gas is cooled before being filtered in ceramic candle filters
- The CaS leaves the reactor with the ashes
- Solids and fines are separated and burned in an atmospheric CFB boiler
- The demonstration plant was operated for 3 years with carbon conversion higher than 95%



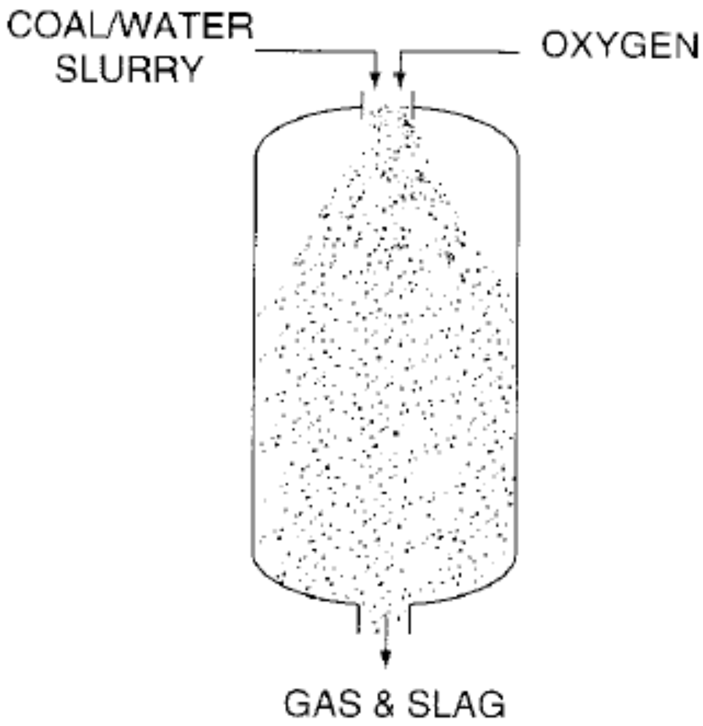
# Agglomerating fluid bed processes

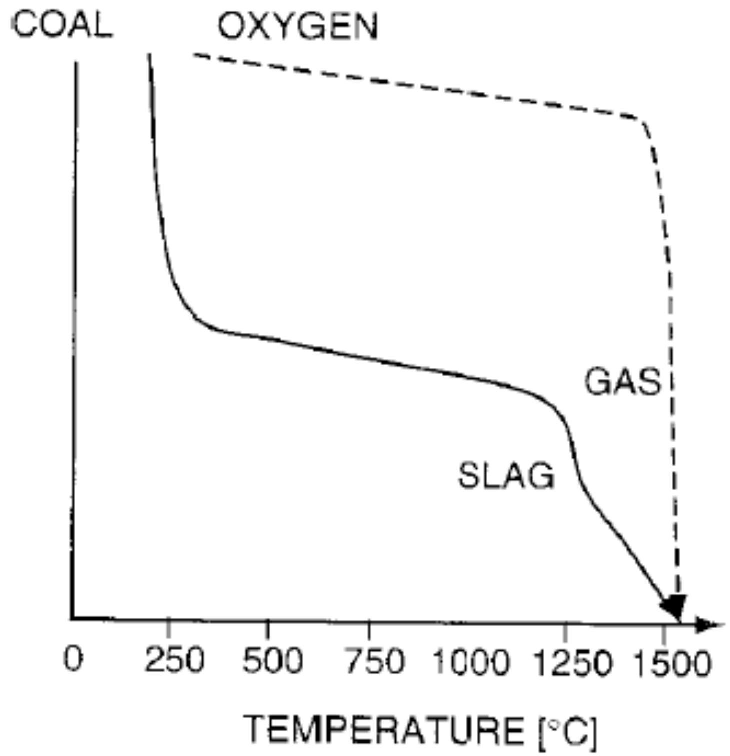
- They are the U-Gas and the KRW (Kellogg Rust Westinghouse) processes
- The idea is to have ashes reaching the softening point to favour their agglomeration and fall at the bottom of the bed
- The separation of low carbon ashes improves the carbon efficiency
- Several U-Gas atmospheric gasifiers were installed in China
- The KRW gasifier has been employed in the 100 MW IGCC Pinon Pine demonstration gasification plant in the US

# Entrained flow gasifiers

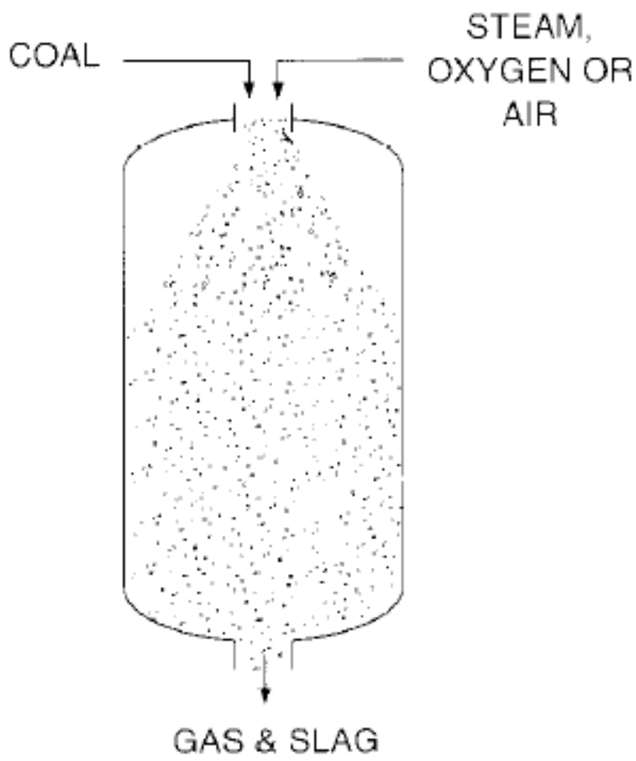
- They can gasify any coal to produce a tar free gas with ash as inert slag
- The fuel enters concurrently with the blast which is pure oxygen or a mixture of oxygen and steam
- They consume a large amount of oxygen but have carbon conversion higher than 99% due to the slagging ashes which is poor with carbon
- They require a fine coal preparation or coal slurry
- Reactor refractory lined or with membrane walls
- The majority of successful gasifiers since 1970 are entrained flow gasifiers
- Pressure is between 20 and 70 bar
- Temperature higher than 1400 °C
- Mainly employed in IGCC

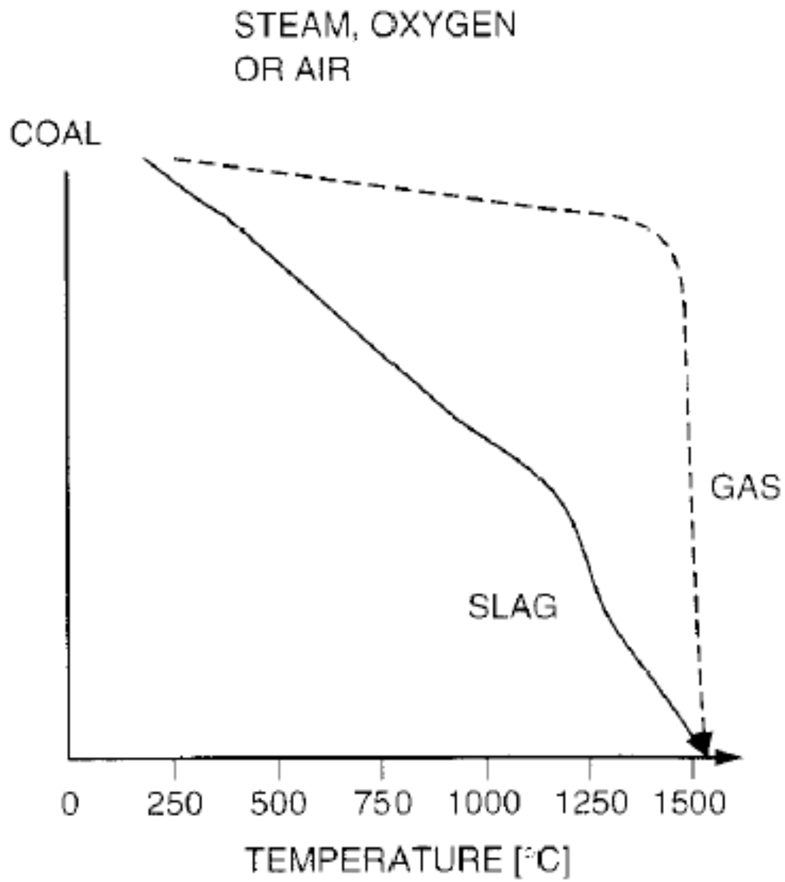
# Texaco coal-water slurry gasifier



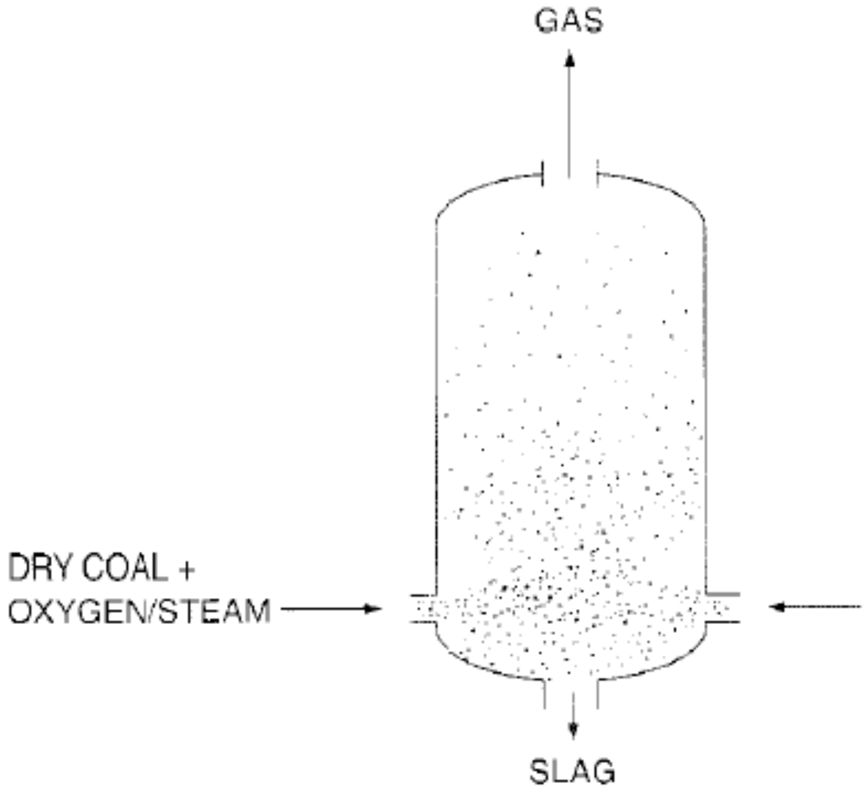



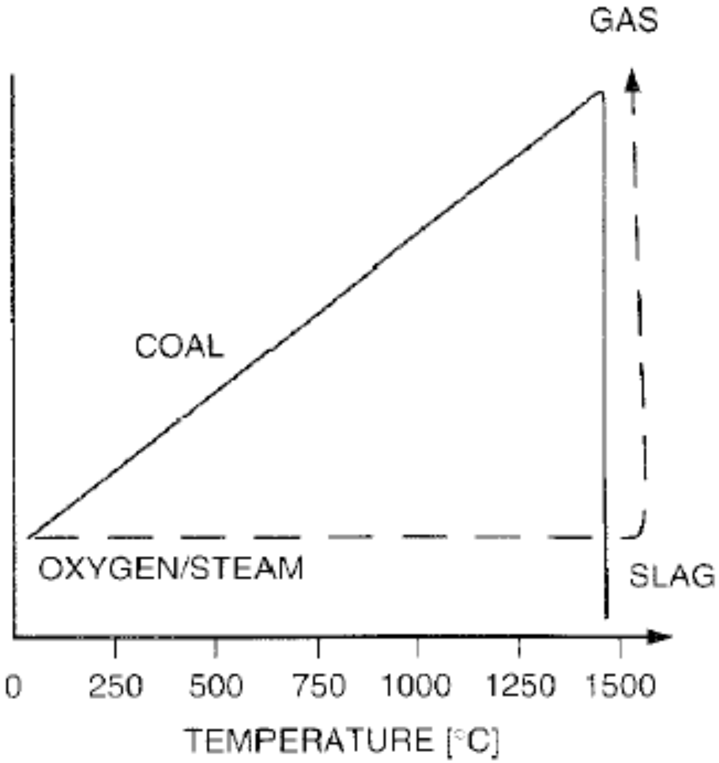
# Noell dry coal upper inlet



# Shell-Prenflo dry coal side inlet



# Entrained flow gasifiers

**Characteristics of Important Entrained-Flow Processes**

| Process | Stages | Feed | Flow | Reactor Wall | Syngas Cooling | Oxidant |
|---|---|---|---|---|---|---|
| Koppers-Totzek | 1 | dry | up | jacket | syngas cooler | oxygen |
| Shell SCGP | 1 | dry | up | membrane | gas quench and syngas cooler | oxygen |
| Prenflo | 1 | dry | up | membrane | gas quench and syngas cooler | oxygen |
| Noell | 1 | dry | down | membrane | water quench and/or syngas cooler | oxygen |
| Texaco | 1 | slurry | down | refractory | water quench or syngas cooler | oxygen |
| E-Gas | 2 | slurry | up | refractory | two-stage gasification | oxygen |
| CCP (Japan) | 2 | dry | up | | two-stage gasification | air |
| Eagle | 2 | dry | up | membrane | two-stage gasification | oxygen |

# Dry Coal feed single stage

- They need the minimum amount of blast
- It is possible to have a very low amount of $CO_2$
- Single stage gasifiers have very low $CH_4$ and very pure gas
- The gas is not sensitive of coal type

# Dry coal feed single stage

**Performance of Various Types of Coals in Dry-Coal Entrained-Flow Gasifiers**

| Coal | | | Gas Analysis of Dry Gas, Mol% | | | | | | Miscellaneous | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Country | Region | Classification | CO | $H_2$ | $CO_2$ | $N_2$ | A | $H_2S$ | $Nm^3$ $CO+H_2$/ton maf coal | $Nm^3$ $O_2$/$Nm^3$ $CO+H_2$ | kg steam/$Nm^3$ $CO+H_2$ |
| Germany | Rhein | Browncoal | 61 | 29 | 8 | 1 | 1 | 0.2 | 965 | 0.33 | 0 |
| USA | North Dakota | Lignite | 62 | 26 | 10 | 1 | 1 | 0.1 | 935 | 0.36 | 0 |
| USA | Montana | Sub-bituminous | 63 | 34 | 1 | 1 | 1 | 0.4 | 1950 | 0.26 | 0.06 |
| USA | Illinois | Bituminous | 61 | 35 | 1 | 1 | 1 | 1.5 | 2030 | 0.25 | 0.09 |
| Poland | typical | Bituminous | 58 | 39 | 1 | 1 | 1 | 0.2 | 2290 | 0.20 | 0.15 |
| S. Africa | typical | Bituminous | 64 | 33 | 1 | 1 | 1 | 0.3 | 2070 | 0.26 | 0.09 |
| China | Datung | Bituminous | 66 | 31 | 1 | 1 | 1 | 0.2 | 2060 | 0.27 | 0.09 |
| India | typical | Bituminous | 62 | 33 | 2 | 1 | 1 | 0.5 | 1730 | 0.31 | 0 |
| Australia | typical | Bituminous | 62 | 34 | 1 | 1 | 1 | 0.3 | 2100 | 0.26 | 0.07 |
| Germany | Ruhr | Anthracite | 65 | 31 | 1 | 1 | 1 | 0.2 | 2270 | 0.26 | 0.13 |

# Dry Coal feed two stages

- The second stage is a non-slagging gasifier
- The first stage is slagging with only parts of the reactants
- The hot gas drives the endothermic reaction in the second non slagging stage where the rest of the fuel is introduced
- There may be some tar formation in the second stage that can be avoided by introducing steam
- Two stage gasifiers require less oxygen and more steam
- The syngas is cooler but with a higher methane and CO2 content

# Coal slurry gasifiers

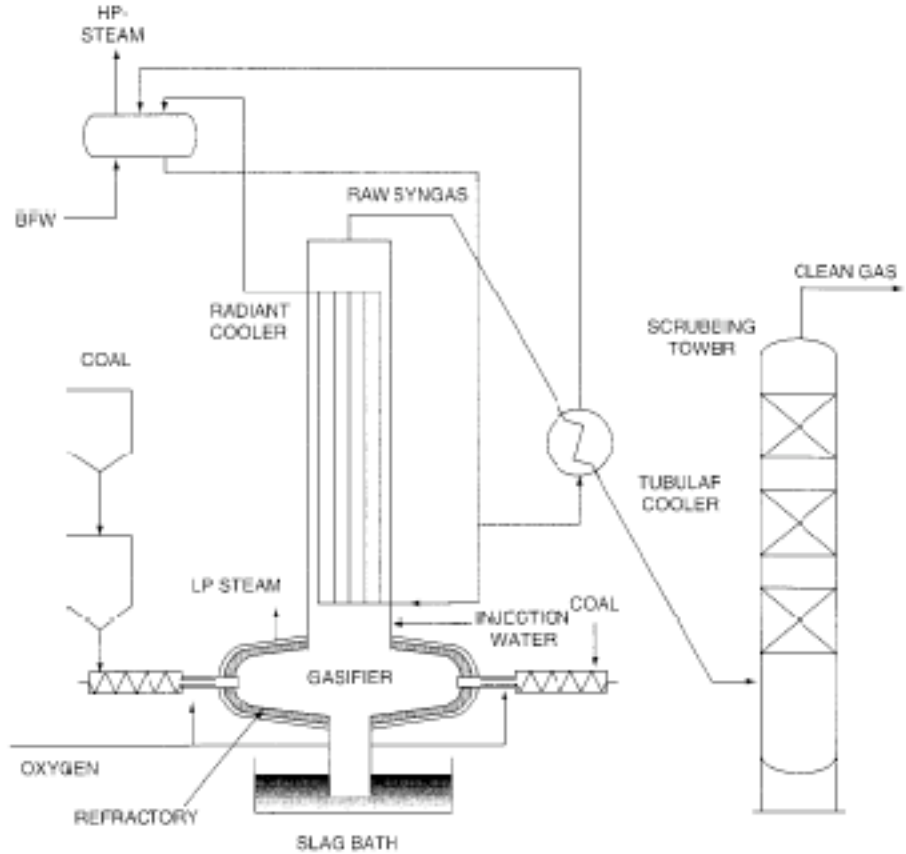
- Introducing a coal-slurry mixture is easier in a pressurized reactor
- Pressure could be as high as 200 bars against 50 bars for lock hoppers
- In single stage gasifiers space has to be provided fro water evaporation
- More hydrogen is present
- High steam flow rates are not required because much heat is subtracted by water evaporation

# Koppers-Totzek process

- The first entrained flow gasifier was built in 1950 at atmospheric pressure
- Commercial units were built in Finland, Greece, Turkey, South Africa
- No new gasifiers of this type were built recently

# Koppers-Totzek process

- Side burners for the introduction of coal and oxygen
- Steam jackets around the reactor
- The first units had two burners for 5000 Nm3/h and later 4 burners for 32,000 Nm3/h
- The syngas leaves at 1500 °C and is quenched with water to 900 °C to avoid slag deposition in the syngas steam generator
- Burners are of the premixed type
- Slag is quenched in a water bath

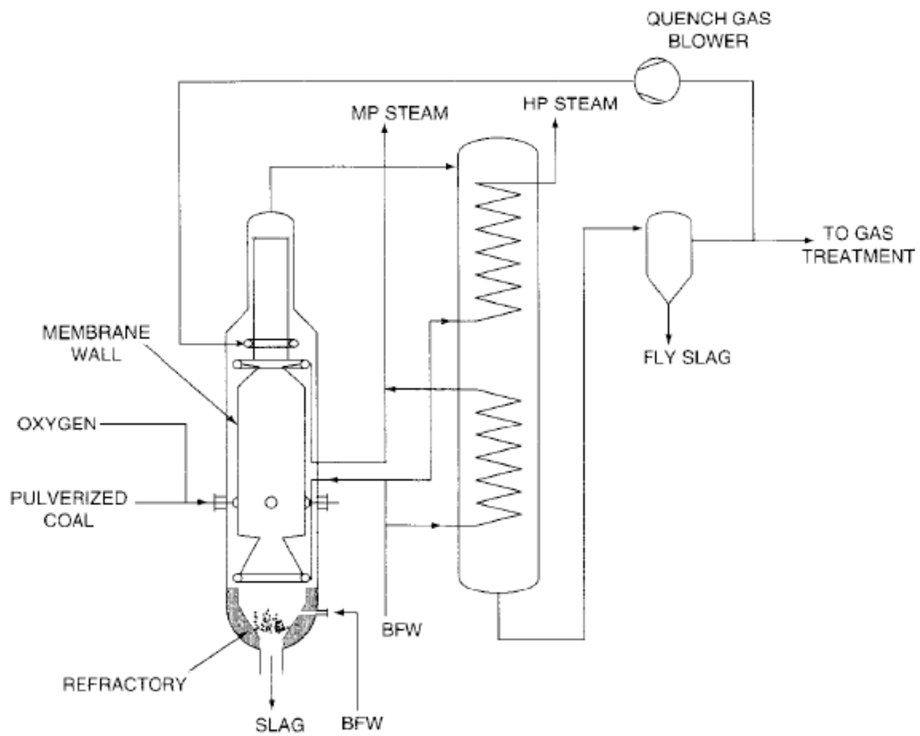


# Shell and Prenflo Processes

- Both are development of the Koppers-Totzek process
- Shell and Koppers began developing together a gasifier, but after some years of cooperation they continued separately
- Two important IGCC plants were built in 1994 and 1997. The first in Buggenum and the second in Puertollano
- Both processes are similar

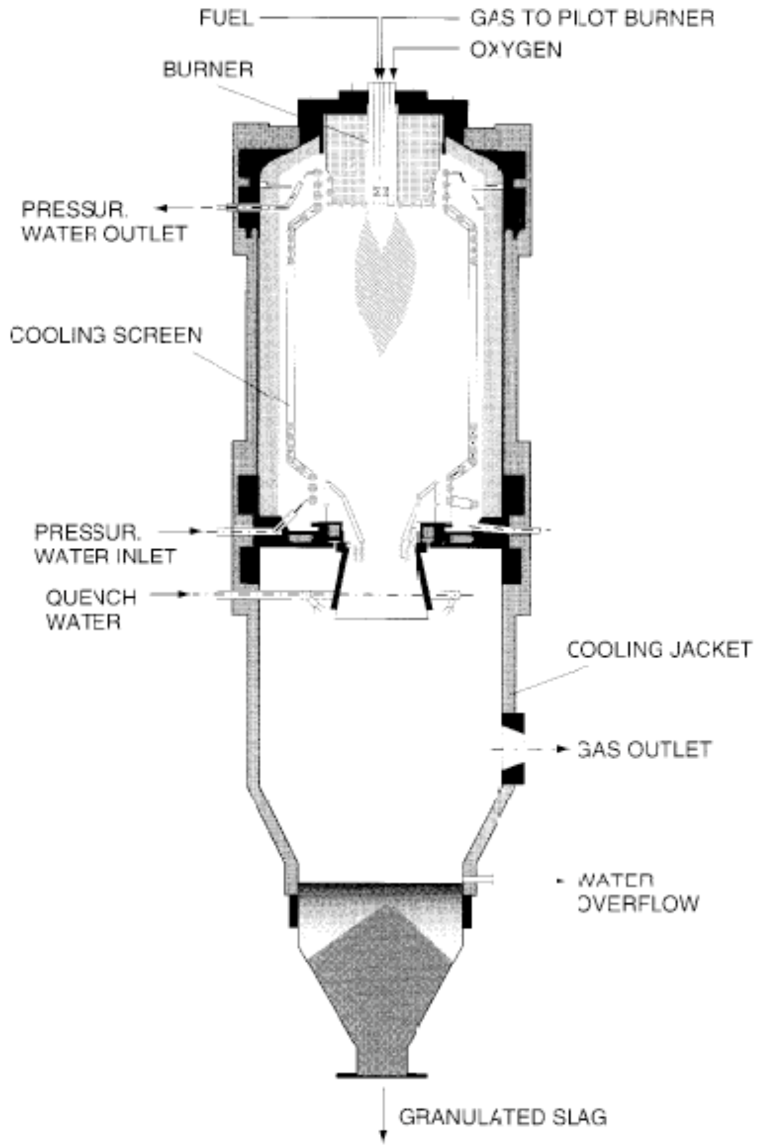
# Shell and Prenflo process

- 4 burners with the fuel carried by nitrogen
- The gas and solid flow is upward
- Coal is ground at 90 μm and mixed with oxygen and steam
- Very fast reactions: 0.5-4 seconds to complete
- Temperature 1500 °C and pressure 30-40 bar
- The gas has two thirds of CO and one third of H2
- The hot syngas is quenched at 900 °C with cold recycle gas
- After the quench the syngas produces steam for the cycle
- At 280 °C the gas is filtered for the solids and half is recycled for quench and half is further cooled



# Noell process

- Developed in Germany in 1975 for coal
- Further developments in 1991 for waste and biomass
- Top fired reactor with a single burner easier to control
- Slag and gas exit in the same direction avoiding slag blockage of burners

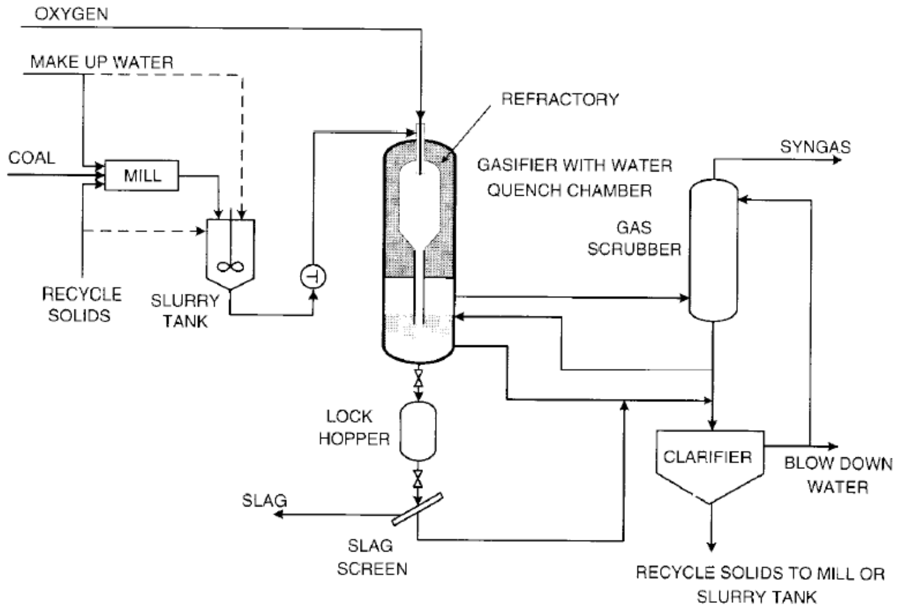


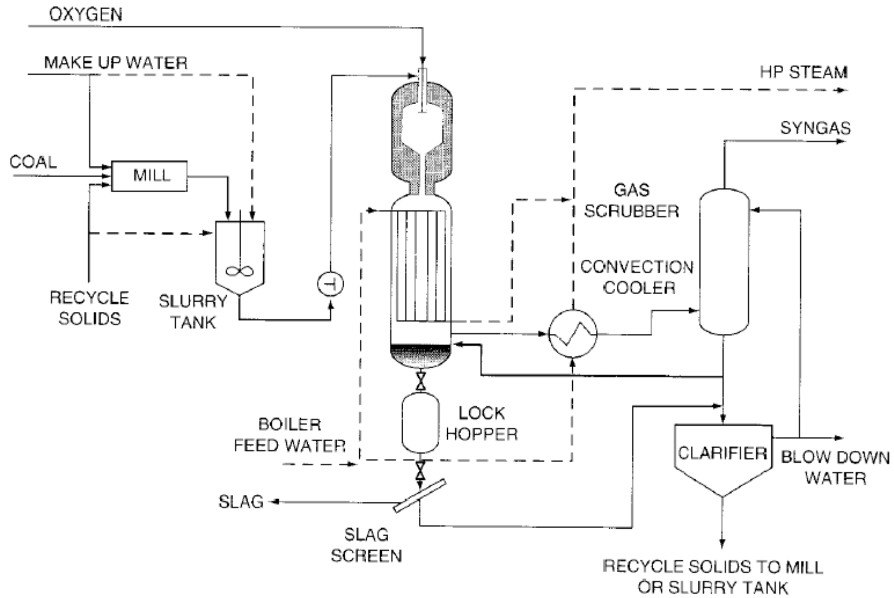
# Texaco process

- Developed in 1940 reached commercialization in 1950
- Two demonstration plants in 1970 and 3 commercial in 1983 and 1985
- 9 more since 1990 in ammonia production and for IGCC

# Texaco process

- The fuel is a coal slurry introduced from top and exits from the bottom
- The reactor is uncooled refractory lined vessel
- Syngas cooling may be either total quench or radiant boiler
- The solid fuel has to be ground at 100 $\mu$m.
- Pressure can be up to 80 bar and temperature reaches 1500 °C
- The oxidant is oxygen
- The gas leaves the quench saturated at 300 °C and the radiant cooler at 760 °C and the convection cooler at 400 °C



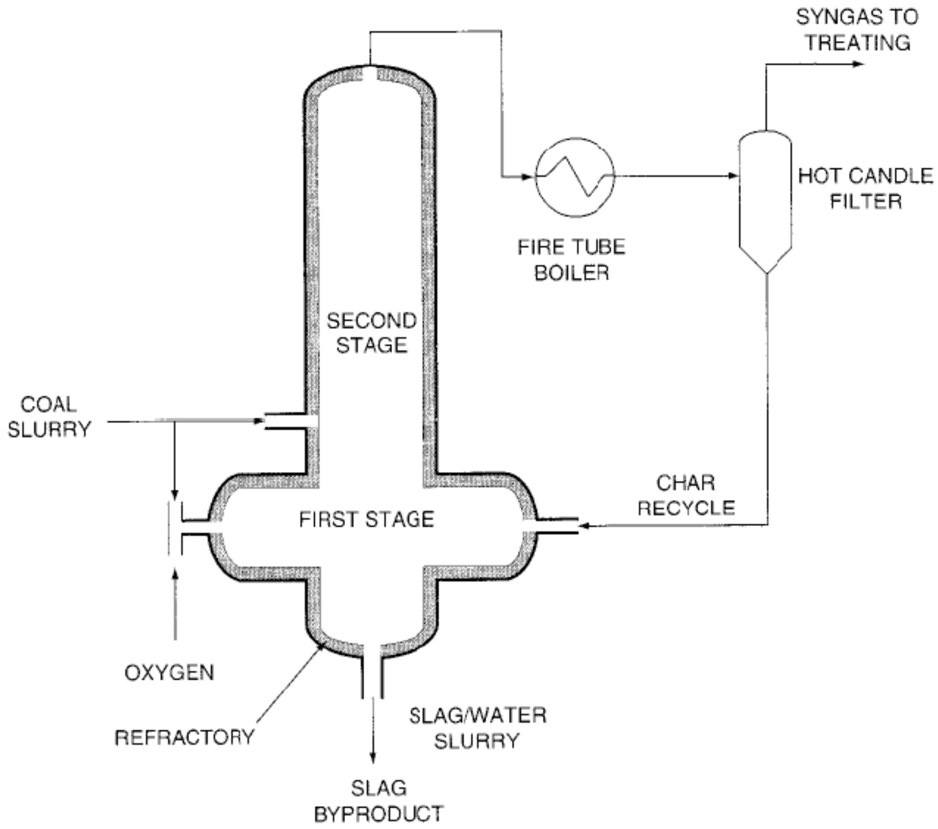



# E-gas process

- Developed by Dow at Plaquemine in 1978 with a 12 t/d of coal water slurry
- This was followed by a 1600 t/d IGCC in 1987
- In 1996 the Wabash River plant with 2500 t/d was started up.
- The E-gas is a two stage coal slurry gasifier for low rank coals

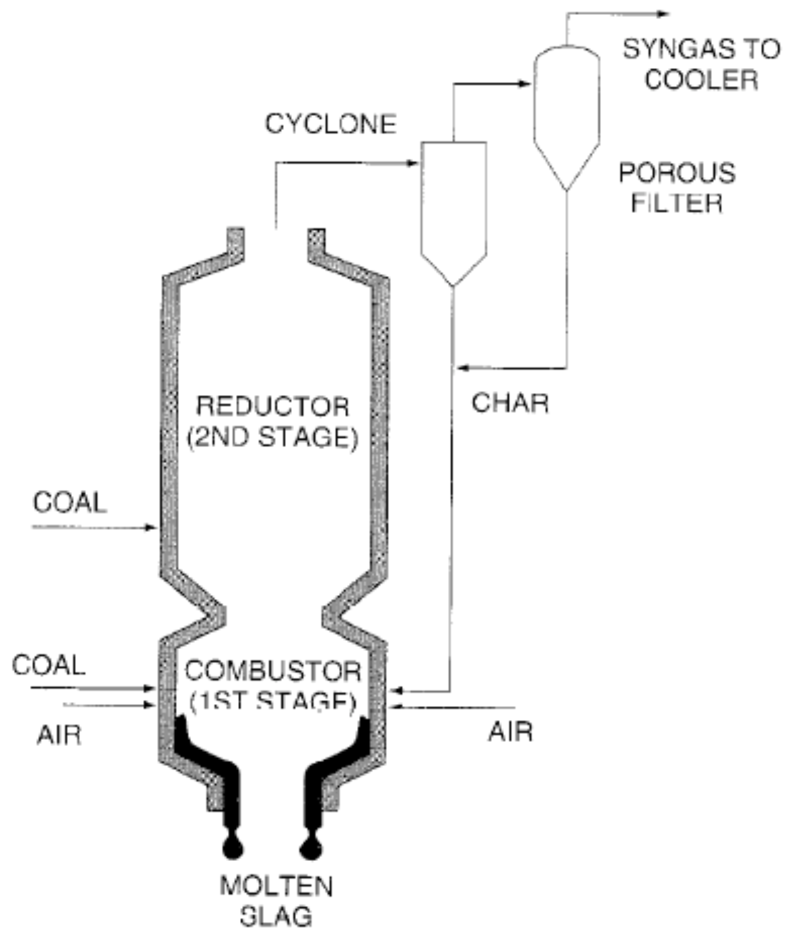
# E-gas process

- The slurry is injected in the first slagging stage and reaches a temperature of 1040 °C
- The mixture passes through a syngas cooler where the char is separated from the gas in a particulate removal unit
- The char is then injected with oxygen and steam in the first stage
- The waste heat form the first stage is used in the non slagging stage to free the feed of all the water and for partial pyrolysis
- The slag is quenched in a water bath



# CCP process

- Developed in Japan by a consortium of enterprises and research institutions
- Demonstration plant to be started up in these years
- It is a pressurized two stage gasifier
- The first combustion stage operates in combustion mode with high temperature
- The oxidant is air enriched with oxygen
- Coal is introduced in the second stage without any further oxidant and the endothermic reaction with the first stage gas provides devolatilization and tar cracking of coal gasification
- Most of the char is gasified and the ungasified part is recycled to the first stage
- Final gas temperature is 700 °C



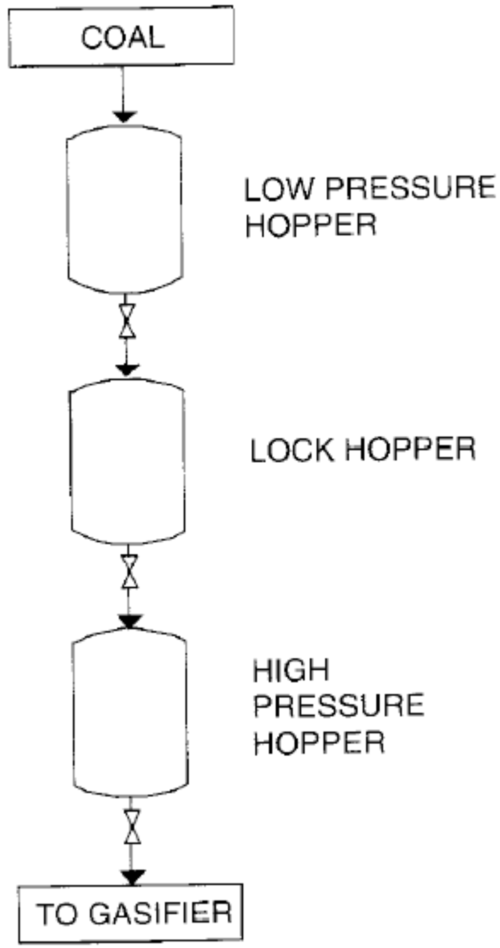
# Auxiliary systems

# Effect of pressure

- It is more convenient to pressurize the feed than the syngas
- However most of the advantages are reached at 15-20 bar and additional pressurizaton is more convenient on the syngas
- Oxygen compressors are available up to 70 bar and oil and coal-slurry pumps can pump up to 200 bar
- Maximum pressure for lock hoppers is 50 bar
- There is no problem for the reactor

# Dry Coal Feeding

- The lock hopper is filled at atmospheric pressure, then is pressurized and the solid is discharged into the high pressure hopper
- When the lock hopper is empty, the pressure is reduced and the upper valve is opened
- When reducing the pressure the solids tend to come out of the system
- Additional problems are created by the discontinuity of the process when the reactor is very fast
- There is concumption of high pressure gas to operate the hoppers



# Dry Coal Feeding

- To transport the solids nitrogen is usually employed, but this contaminates the syngas
- For every kg of coal at 30 bar 0.09 kg of $N_2$ are necessary
- If the $N_2$ is negative for the chemical process then it is better to operate the gasifier at lower pressures and increase the syngas pressure
- In some cases syngas can be used for solid transport
- $CO_2$ can be a viable alternative if it is not an additional cost where a CO shift is present and $CO_2$ is removed by the syngas

# Coal slurry

- Coal water mixtures can have 60-70% coal
- Most water is not needed in the process and takes up heat from the reactions
- Oxygen consumption increases
- Preheating the slurry reduces the heat transferred to the water and improves atomization
- If less heat is subtracted by water, the gasification space is larger and the cold efficiency will increase
- Heated water will expand

# Reactor design

- Fixed bed gasifiers seem simpler, but they need high temperature moving systems inside the reactor for distrbuting the coal and the ashes
- Fluid bed systems are complex in the fluidization part. But normally they are not pressurized and ashes are at temperatures below melting point
- Entrained flow gasifiers are the most complex because they work at high temperatures and pressures

# Temperature protection

- Refractory lining are generally made with three layers:
  - The inner layer is made of corundum bricks (99% $Al_2O_3$)
  - The middle layer is castable bubble alumina
  - The outer layer is silica firebrick
- The insulation must avoid the formation of condensation between the insulant and the steel walls
- With oil gasifiers $V_2O_5$ formation is to be prevented because it is an aggressive liquid that forms during startup at 700 °C
- With coal there are problems of chemical attack of the molten slag and the silica compounds in the coal
- Fluidized beds are more prone to erosion from dry ashes
- Biomass gasification has the problem of molten ashes in fluid beds and the presence of sand in dual stage reactors

# Temperature protection

- An alternative to refractory are membrane walls
- The membrane consists of high pressure tubes in which steam is generated connected by flat steel bridges welded together
- Heat losses are higher than in refractory lined walls
- The back f the membrane has to have the same pressure as the gasifier
- In some cases the jacket construction can simplify the pressure distribution between the gasifier and the external shell

# Burners

- Most of the burners are of the co-annular type where reactants are fed through axisymmetrical annular openings
- The reactants are seldom premixed to avoid pre-combustion or flash-back
- The burner front has to be cooled with water
- The start up of pressurized gasifiers is imortant because the characteristics of the burner are different at ambient and pressurized conditions
- Start up procedures are quite long and gasifiers need to be used as base load power generation systems or in continuous chemical processes

# Syngas Cooling

- Syngas leaves the gasifier at temperatures varying from 550 to 1600 °C
- The syngas is generally contaminated with various components that must be removed before the final use of the syngas
- There is the necessity to cool the syngas and the heat can be used for heating water or generating steam
- When cooling entrained gasifiers syngas the ash will pass through a state when it is sticky and the syngas should be cooled as quickly as possible to 900°C to have the ash dry

# Syngas cooling

- In the fluid beds the temperature does not cause concerns but the fly ashes can cause erosion in the syngas coolers and when limestone is used, CaO can react back with CO2 in the gas to give CaCO3 which can also foul the cooler
- With biomass the problems are linked to the presence of corrosive ashes rich in alkali that may condense between 600 and 900 °C
- In fixed bed gasifiers the presence of tars can foul the coolers if the temperature falls below condensation temperature

# Quenching

- In entrained flow gasifiers there are the worst conditions for the slagging nature of the ashes
- There are four types of syngas coolers:
  - Radiant cooler
  - Water quench
  - Gas quench
  - Chemical quench

# Radiant cooler

- It is difficult to avoid that sticky ashes attach to the cooler surface
- The coolers are difficult to clean because only the surface of the vessel can be used for heat exchange
- The heat can only be used to generate steam
- The surfaces are very large and the size of the cooler has to extend a lot in height

# Water quench

- The gas can be quenched by evaporation of water in the gas
- Partial quench is when the temperature is lowered to 900 °C and total quench is when the gas is saturated
- If the quench is partial there is some remaining heat to be recovered for generating steam
- Texaco has always used total quench
- In ammonia or hydrogen plants having additional water can be advantageous because no additional steam is necessary
- There is a driving force for the CO shift reaction to $CO_2$ thus increasing the $H_2/CO$ ratio

# Gas Quench

- Gas quench is used in the Shell and Prenflo gasifiers
- The syngas cooled in the cooler and freed of solids is partially mixed with the new syngas to reduce its temperature from 1500 to 900 °C
- Quenching with gas is limited to 900 °C to reduce the amount of syngas recycle

# Chemical Quench

- In the chemical quench the sensible heat in the gas leaving the first stage of an entrained flow gasifier is used in the endothermic water gas reaction to gasify the second stage
- The heat absorbed is sufficient to cool the gas such that the ash in the second stage is dry
- Injecting coal in the second stage has the disadvantage that some tars will form

# Syngas cooling

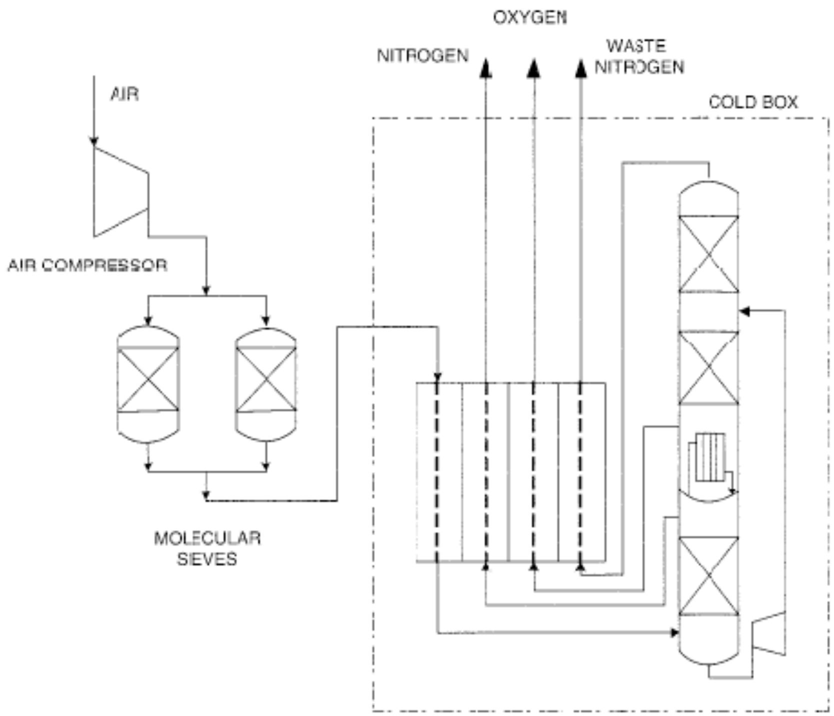
- After quenching the syngas has to be cooled to lower temperatures for additional gas treatment
- In order to remove all the solids the temperature should be lower than 500 °C and to remove acid gases and ammonia the gas has to be cooled to ambient temperature
- This is possible only with a second quench
- Syngas coolers may have water tubes or fire tubes

# Air separation units

- Air separation units (ASU) are very important in gasification plants to produce oxygen from air
- ASU cost 10-15% of the overall plant and the power required fo compression 5-7% of the generated power in IGCC
- The main process is cryogenic separation but membranes are also used

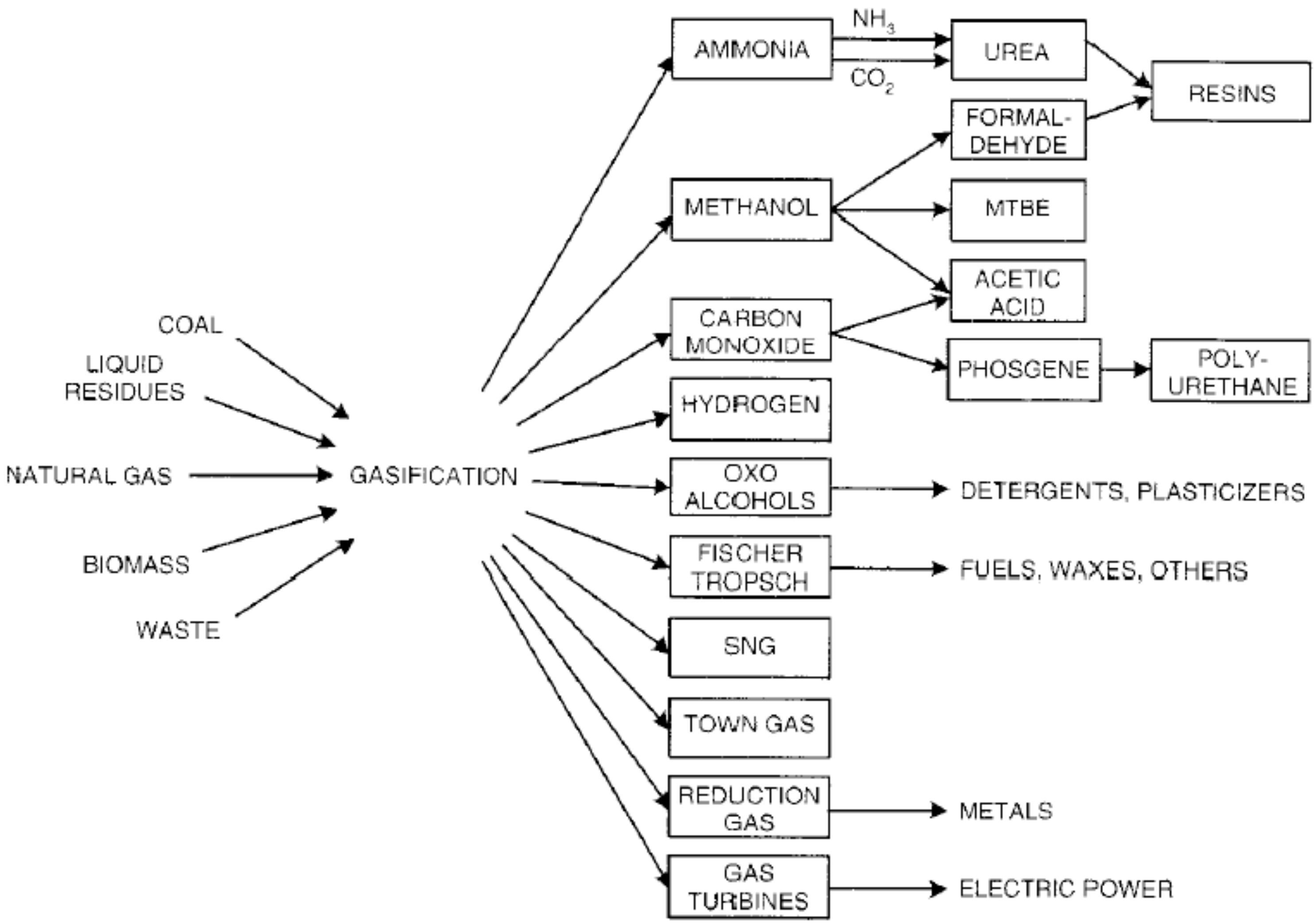
# Cryogenic processes

- In cryogenic processes air is compressed, dried and cooled to liquefaction temperature
- Liquid air is then distilled in oxygen and nitrogen



# Applications

# Applications of Gasification



# Chemical applications

- Ammonia synthesis
  - 160 Mt/y are produced by steam reforming of natural gas
  - 10 Mt/y by gasification of coal and heavy oil
- Ammonia synthesis takes place at high pressure (over 200 bar) with iron catalyst and with N2 and H2 in proportions 1 to 3
- The gasification process must include:
  - Tar and volatiles removal
  - CO shift
  - CO2 removal
  - Desulfurization
  - Final removal of water
  - Adjustment of N:H ratio

# Chemical applications

- Methanol production
  - 3.3 Mt/y or 9% of the total production is made with coal gasification
  - Two thirds of the production is used to produce formaldheyde and MTBE (for gasoline)
- Methanol synthesis si done with a gas mixture of CO and 2H2 and CO2 and 3H2 giving CH3OH
- Optimal conditions are for the stoichiometric ratio

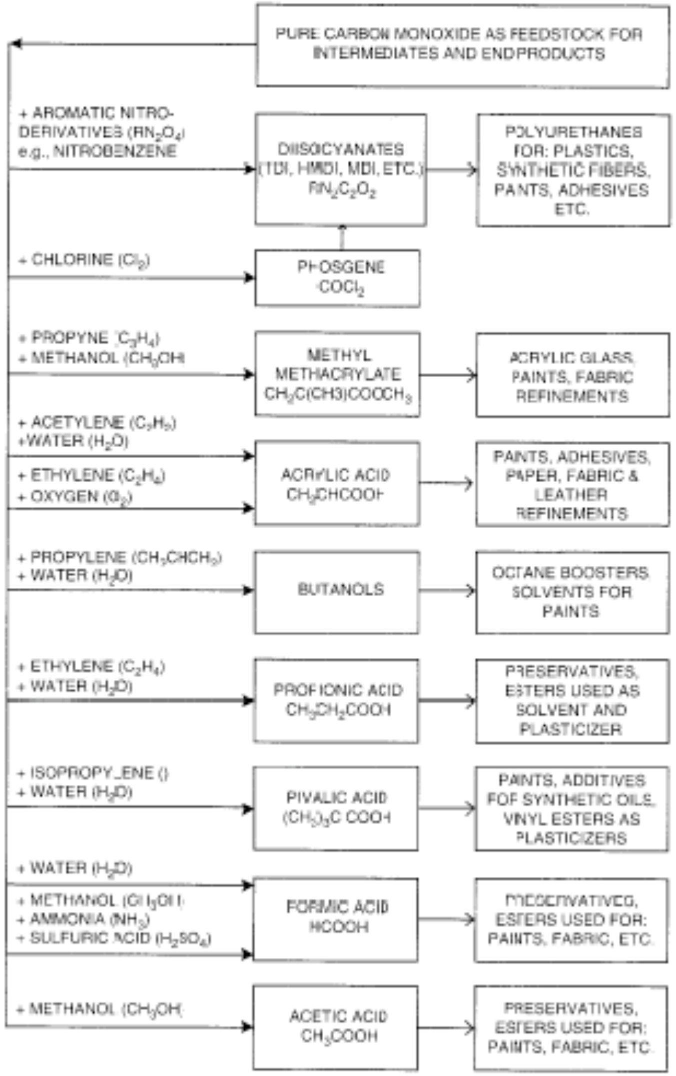
$$\frac{H_2 - CO_2}{CO + CO_2} \qquad 2.03$$

# Chemical applications

- Hydrogen is used in:
  - Petroleum refineries 20,000 to 100,000 Nm3
  - Food industry 1000 Nm3/h
- Hydrogen production is 16 MNm3/h of which 500,000 Nm3/h are produced by gasification
- Many processes require high purities up to 99.9999 % in silicon wafers production

# Chemical applications

- Carbon monoxide has several applications



# Fuel applications

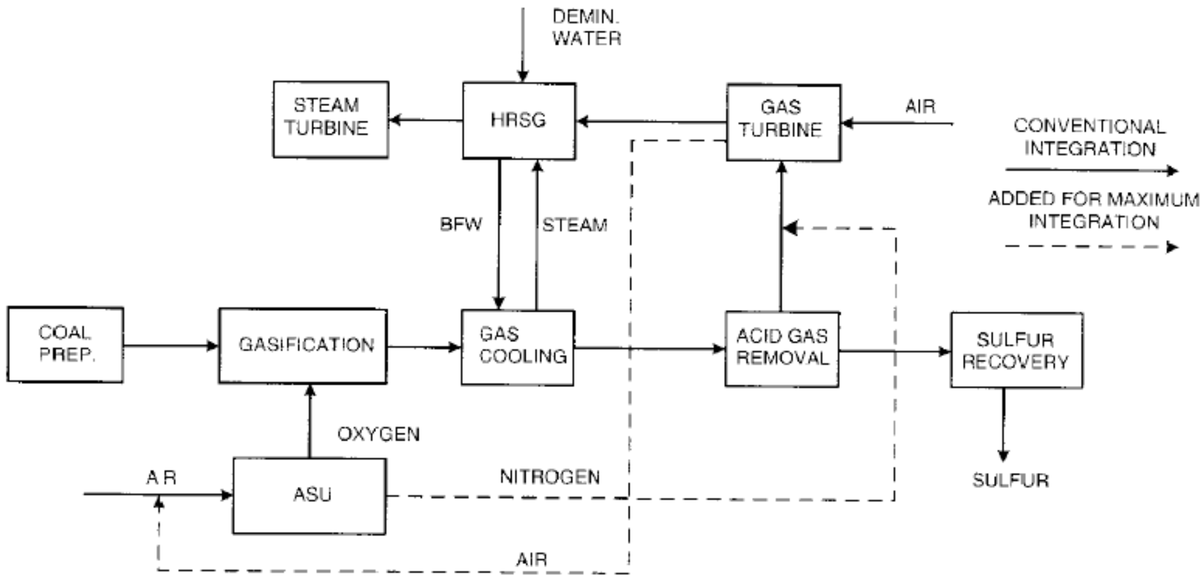
- The only place in the world where coal is used ot produce liquid fuels is South Africa.
- Here the gasoline is produced as a Fischer Tropsch fuel from coal gasification
- The only application of coal to syngas to have a synthesis natural gas is  in North Dakota

# Power

- The IGCC (Integrated Gasification Combined Cycle) is a combination of a gasifier with a combined cycle
- Advantages:
  - Use of high efficiency cycles
  - Use of clean gaseous fuels derived from solid fuels or oil
  - Integration of the gasifier and CC further improves efficiency
- Disadvantages:
  - Lower efficiency than using natural gas
  - Complicated integration and clean up systems for the syngas
  - Higher capital costs

# Integration of the gasifier

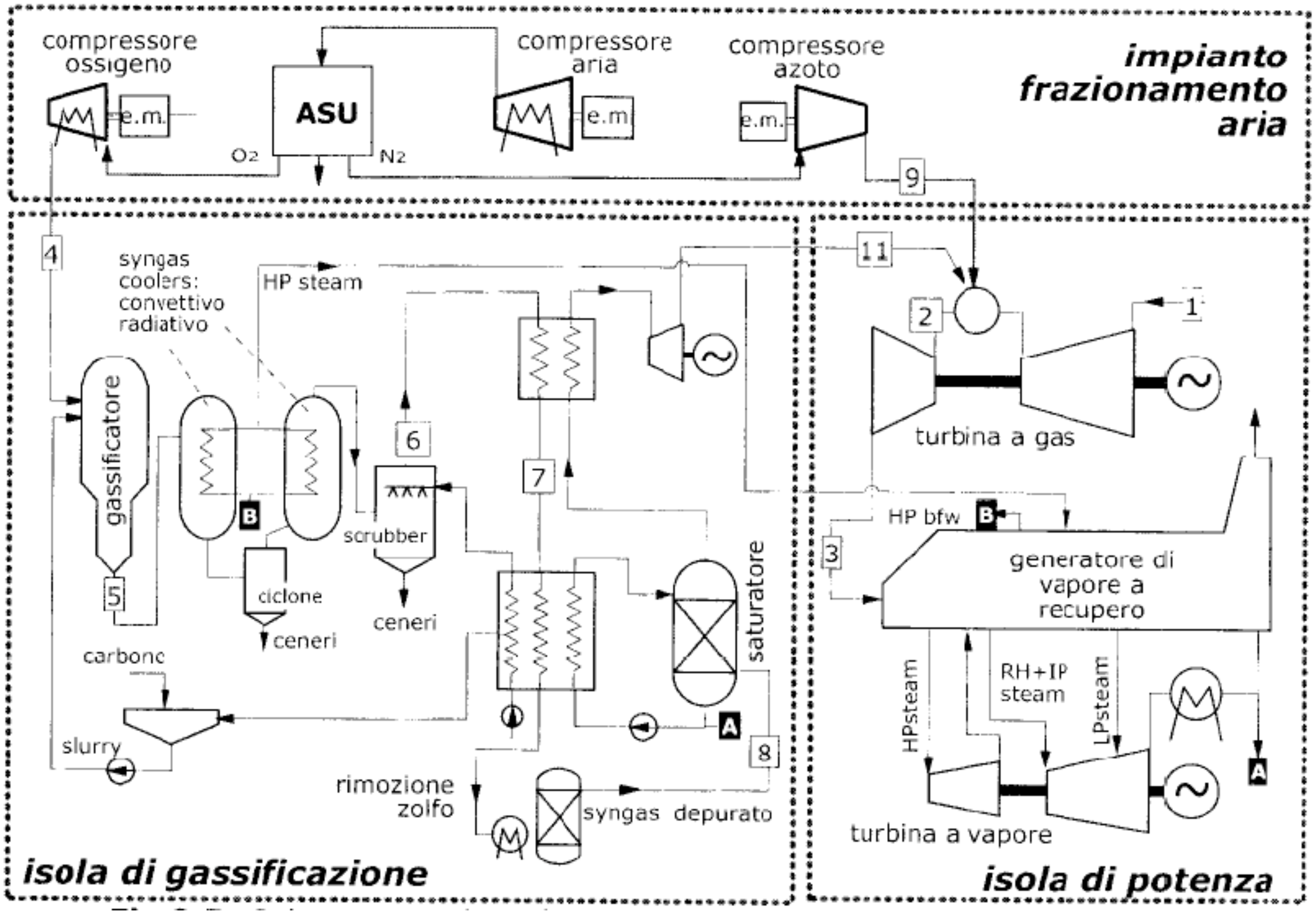
- There are three levels of integration
  - Steam generation
  - Air separation unit (ASU)
    - The ASU can be totally fed by the compressor of the GT or partially fed by a second compressor
  - Fuel gas expansion



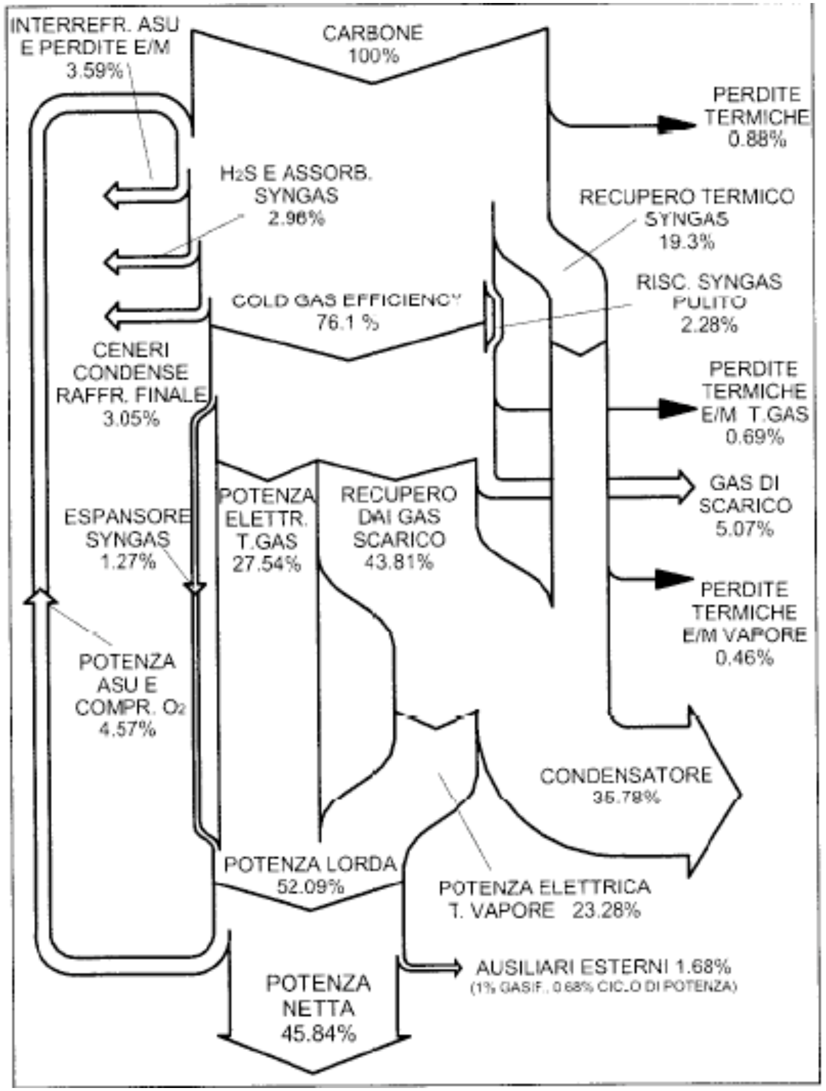
# Integration means

- The steam section of the IGCC receives a thermal input from:
  - Gas turbine exhaust
  - Cooling processes of syngas
  - Cooling of the gasifier
  - H2S produces steam
  - The ASU has to be cooled
- But steam is required in the gasifier
  - As gasifying agent
  - To dry coal
  - In acid gas removal processes and gas cleaning
- The ASU can be fed by compressed air form the GT compressor
  - The ASU works under pressure and produces oxygen at 3 bar

# Integration



# Energy transfers



# Efficiency

- The efficiency of a gasifier is approximately 80%
- The efficiency of the CC can be 60%
- The maximum efficiency is the product of the efficiencies and is 48%
- Then we have to consider the efficiency of ASU and the gas treating

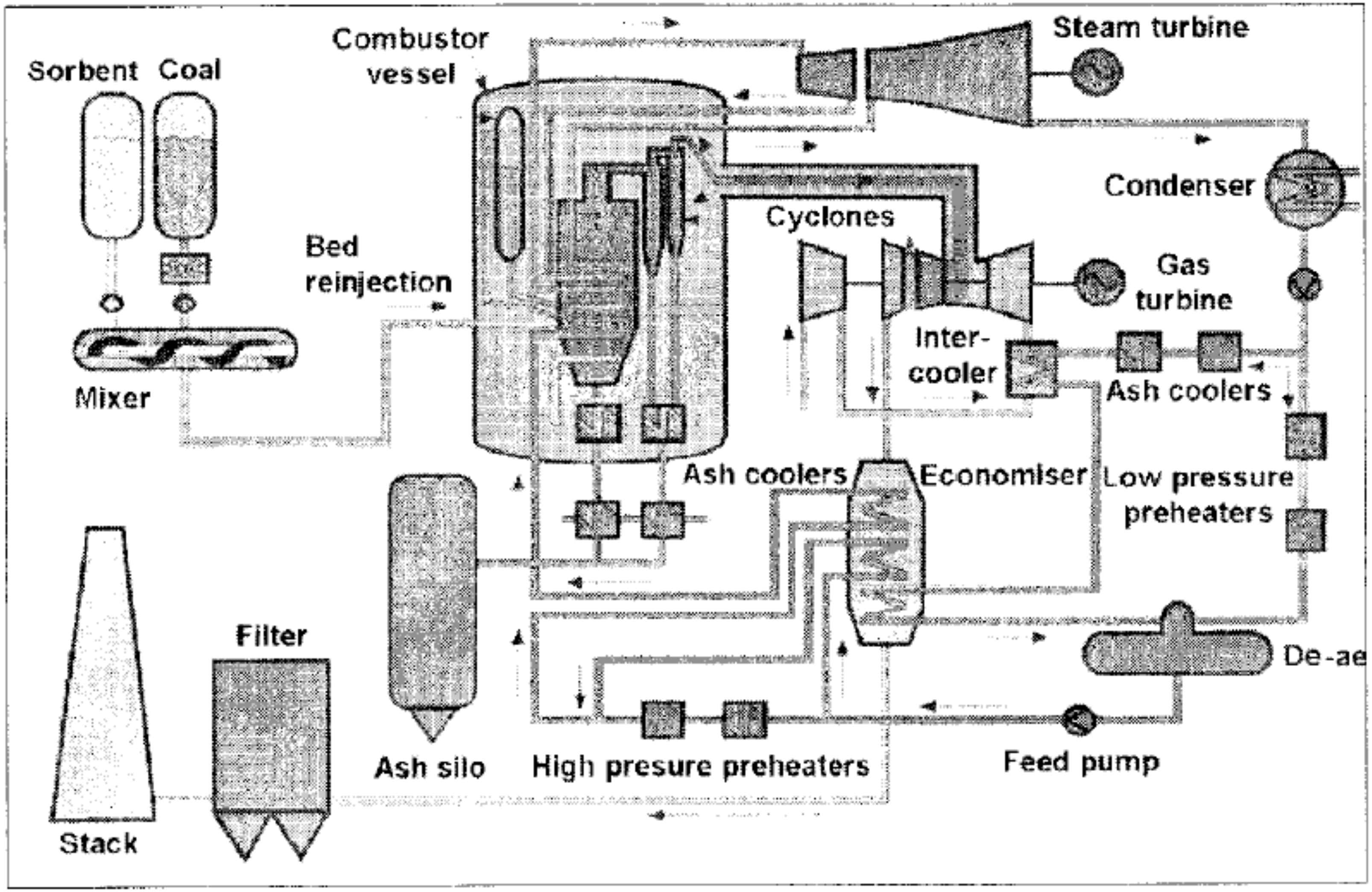
# Performance of IGCC

**Efficiencies of Various IGCC Power Stations with and without $CO_2$ Removal Facilities**

| Process | | | Fuel Gas Treating | | Flue Gas Treating | |
|---|---|---|---|---|---|---|
| Feed | Gasifier conditions (bar/°C) | Syngas cooling | Without $CO_2$ removal | With $CO_2$ removal | Without $CO_2$ removal | With $CO_2$ removal |
| Slurry | 64/1500 | Water quench | 37.8 | 35.5 | 43.0 | 39.7 |
| Slurry | 64/1500 | Gas quench | 43.6 | 39.4 | 43.1 | 39.8 |
| Extreme preheat slurry | 64/1500 | Gas quench | 48.8 | 43.7 | 49.6 | 46.3 |
| Dry | 32/1500 | Gas quench | 50.0 | 44.5 | 50.6 | 47.3 |
| Dry | 32/1500/1100 | Coal quench | 50.9 | 45.5 | 51.5 | 48.2 |
| Dry | 32/1100 | Water quench | – | – | 51.5 | 48.2 |
| Supercritical steam power plant | | | | | 45 | 41.7 |

*Note: Efficiencies based on standardized, idealized conditions of Appendix E.*

# PFBC


Combustor vessel
Sorbent
Coal
Steam turbine
Condenser
Cyclones
Bed reinjection
Gas turbine
Inter-cooler
Mixer
Ash coolers
Ash coolers
Economiser
Low pressure preheaters
Filter
De-ae
Ash silo
High presure preheaters
Feed pump
Stack

# PFBC

- Advantages
  - Combustion instead of gasification
  - No need for ASU
  - No need of syngas treatmenr
- Disadvantages
  - Higher costs
  - Lower efficiency
  - Less experience

# PFBC with partial gasification